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Optimal Airtanker Location in Alberta

by

© ROBERT GEORGE NEWSTEAD

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Optimal Airtanker Location in Alberta submitted by ROBERT GEORGE NEWSTEAD in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in GEOGRAPHY.

ABSTRACT

The forest resource is an important asset to the social and economic well-being of Alberta. As a consequence, one of the major objectives of the Alberta Forest Service (AFS) is to minimize the negative impact of wildfire on this resource base. In striving to achieve this objective, the airtanker program has become an important and integral component of the AFS presuppression effort. Centralized administration of this fire control capability lends itself to investigative opportunities, particularly in the area of location-allocation modelling.

The objective of this thesis is to introduce and test a location-allocation model designed to optimize the location of four groups of airtankers in response to prevailing fire occurrence patterns during 23 distinct time periods during the 1974 fire season. This model offers a unique contribution to the airtanker literature in that it optimizes group locations among 11 potential bases and allocates fire occurrences to these bases as it trades-off aggregate base-to-fire distance minimization with maximization of the "value-at-risk" and number of fires served.

It was found that, in comparison with a fixed attack range criterion, the adoption of three fire hazard-dependent attack ranges resulted in the determination of superior base locations in that the former solution tended to overestimate airtanker effectiveness potential. Furthermore, when the

consequences of maintaining an inflexible basing schedule were investigated, it was shown that locational flexibility of airtanker groups from one time period to the next yielded superior base locations when evaluated in the variable-range model.

Finally, optimal base locations generated by the variable and fixed-range models were compared with the actual base locations occupied by the four groups during the 1974 time periods. It was found that the modelled locations were better than the actual locations in providing greater "value-at-risk" and fire coverage and lower average base-to-fire initial-strike distances. Once again the optimal variable model solution offered slightly greater overall superiority over the actual schedule than the fixed-range solution, which in turn seemed to more closely approximate the results of the actual group locations for the season.

Some of the various operational constraints which influence the capacity of the model to synthesize the airtanker location problem are discussed. This sets the stage for introduction of future model refinement possibilities and additional research opportunities.

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I. INTRODUCTION

As a force of nature, fire has been both a friend and enemy of man since his earliest beginnings. Since early post-glacial times in Alberta, forest fires have ranked high on the list of natural hazards that have brought about changes in the landscape and the lives of its residents. The forest and prairie ecosystems upon which man has become so dependent in this region have been altered many times by fire both as a natural phenomenon and as a tool of man.

Today more than ever before man must contend with wildfire as a destructive element. He has increasingly imposed his own perceived values on the forest resources and it has become even more important that these values be protected from loss or degradation by fire. The social, environmental and economic values of Alberta's forest resources are well recognized. Accordingly, the resource values associated with the forest land base deserve the highest levels of management and protection that can be afforded them for the sake of their well-being now and in the future.

A. Problem Statement

Alberta's forests cover roughly two-thirds of the province. Of this area, approximately 93% (412,000 km²) is provided with some level of protection from wildfire (Miyagawa 1974). Between 1961 and 1974 an average of 584

fires burned 53,000 ha annually at an estimated value loss of $3.7 million per year. Average annual suppression costs during this period, expressed in 1975 dollars equalled $3.6 million (McDonald 1976). These statistics serve to support the continuing need for an organized and effective initial attack capability ready to minimize annual costs and losses resulting from wildfire occurrence.

Since its inception in 1930 the Alberta Forest Service (AFS) has strived to achieve its objective of managing the province's forest lands in a manner ensuring a perpetual supply of benefits and products while maintaining an environment of high quality (McDonald 1977). In order to attain this objective the Forest Protection Branch has established as its primary objective the protection of Alberta's forests from damage and destruction by fire, insects or disease as well as the provision of meteorological, emergency communications and survival services as an adjunct to the protection services (McDonald 1977).

Toward achieving this objective, a major goal has been to minimize the loss of forest areas to fire and to control any major insect and disease infestations that may develop. On the fire front the aim is to hold the annual burned area to within one-tenth of one percent of the forest land area (McDonald 1977). This has meant that the AFS has had to respond to the fire problem in four specific areas of activity. These are: (1) fire prevention to reduce the level

of man-caused fire incidence, (2) fire detection to discover all fire starts at 0.1 ha or smaller, (3) presuppression to maintain a state of preparedness of manpower and equipment, (4) and a suppression capability to attack all fires within one hour of notification and to contain them at 1.2 ha, or less, in size (McDonald 1977).

The AFS maintains a three-level administrative structure with operational functions at the provincial, forest and district levels. Provincial headquarters (PHQ) is located in Edmonton and is responsible for province-wide policy and planning in the areas of fire operations, air administration including aircraft dispatch, prevention and detection, program liason and analysis, telecommunications and fire weather (Figure 1). The actual day-to-day forest protection and fire suppression activities are conducted at the forest level throughout the ten such administrative jurisdictions in the province. During the course of the April 1 to October 31 fire season PHQ provides support services to the forests on the basis of their daily requirements. This level of service is augmented when the demands of any given period of fire suppression activity drain locally available resources. Specifically this involves contract and casual charter aircraft allocations, supplementary communications and fire fighting equipment, paracargo services, weather forecasting, specialized fire detection services, coordination of inter-forest manpower and equipment exchanges and a host of other related support

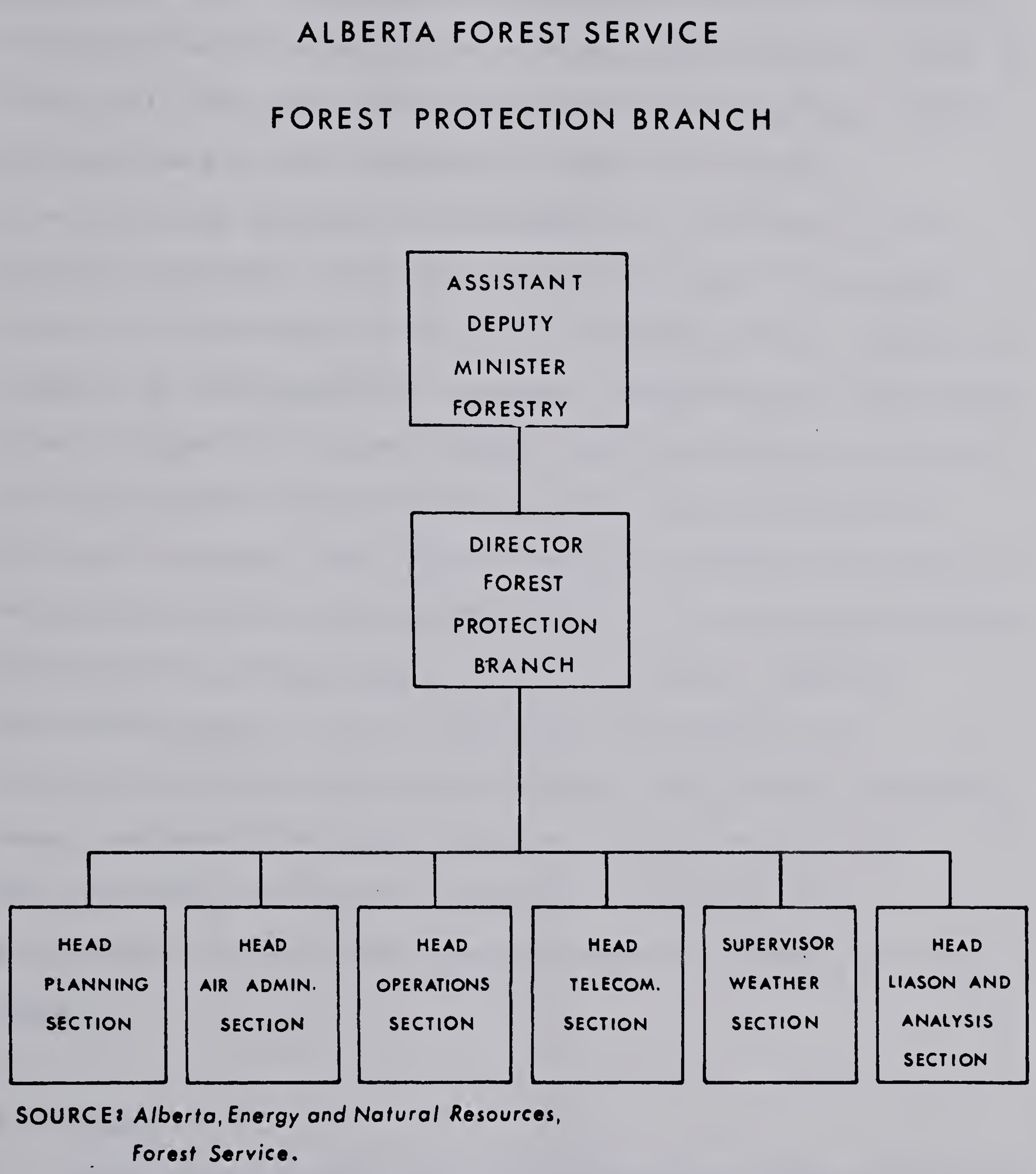


Fig. 1. Organization Chart - Alberta Forest Service, Forest Protection Branch Headquarters.

and service activities.

Centralized control of the province's aircraft resources including the bomber groups lends itself to the application of resource allocation optimization techniques. The speed and flexibility of a fixed-wing airtanker fleet is such that inter-base transfers of designated groups can be accomplished on short notice in order to respond to province-wide changes in the severity of regional fire hazard conditions. Only at headquarters can the required level of fire hazard information be gathered and compiled in support of knowledgeable airtanker dispatches between bases. Once assigned to a given forest, the day-to-day role of any given group will be monitored by the forest protection officer-in-charge, but PHQ retains final authority over all dispatches within and between forests. As a consequence the development and application of an airtanker location optimizing model is well suited to the present AFS centralized administrative structure. This allows the daily needs and wants of several regional authorities to be analyzed and traded-off in the best interests of a provincial initial attack program over the course of a fire season.

B. Purpose

This thesis deals with the presentation and application of a location-allocation (L-A) model which treats one aspect of the initial attack program in Alberta, specifically the

optimal positioning of airtankers in response to prevailing fire hazard conditions. The primary objective is to propose a mathematical model which will determine where a limited number of airtanker groups can be best located in such a way that base-to-fire strike distances are minimized while offering the greatest possible level of protection in terms of the resource values at stake.

Following presentation and discussion of such a model, its performance is demonstrated using empirical fire occurrence data for the 1974 fire season. The model is run for twenty-three distinct time periods to assess its response to short-term changes in fire occurrence patterns. The model incorporates two predefined fire hazard related categories governing maximum airtanker attack range. The manner in which these limitations influence the results is discussed. Finally, the overall results are compared with the outcome of the actual bomber group positioning schedule for 1974. This is not a predictive model at the present stage of development and cannot be used as such unless advanced knowledge of expected fire locations is available.

The model does not account for differences in the productive capacities of the airtankers under consideration, nor does it recognize the actual or potential dynamics of the fire circumstances at the target sites. There is no attempt to predict the nature of the fuels, weather, or causal agents that might contribute to the behavior or outcome of any given fire event. The mechanics of the

location-allocation algorithm are simplified as a means of concentrating on the spatial aspects of the model - that is, "where could four airtanker groups be best located during specific time intervals to optimize their opportunity to take initial strike action in response to changing fire occurrence patterns?"

C. Forest Fires in Alberta

Occurrence

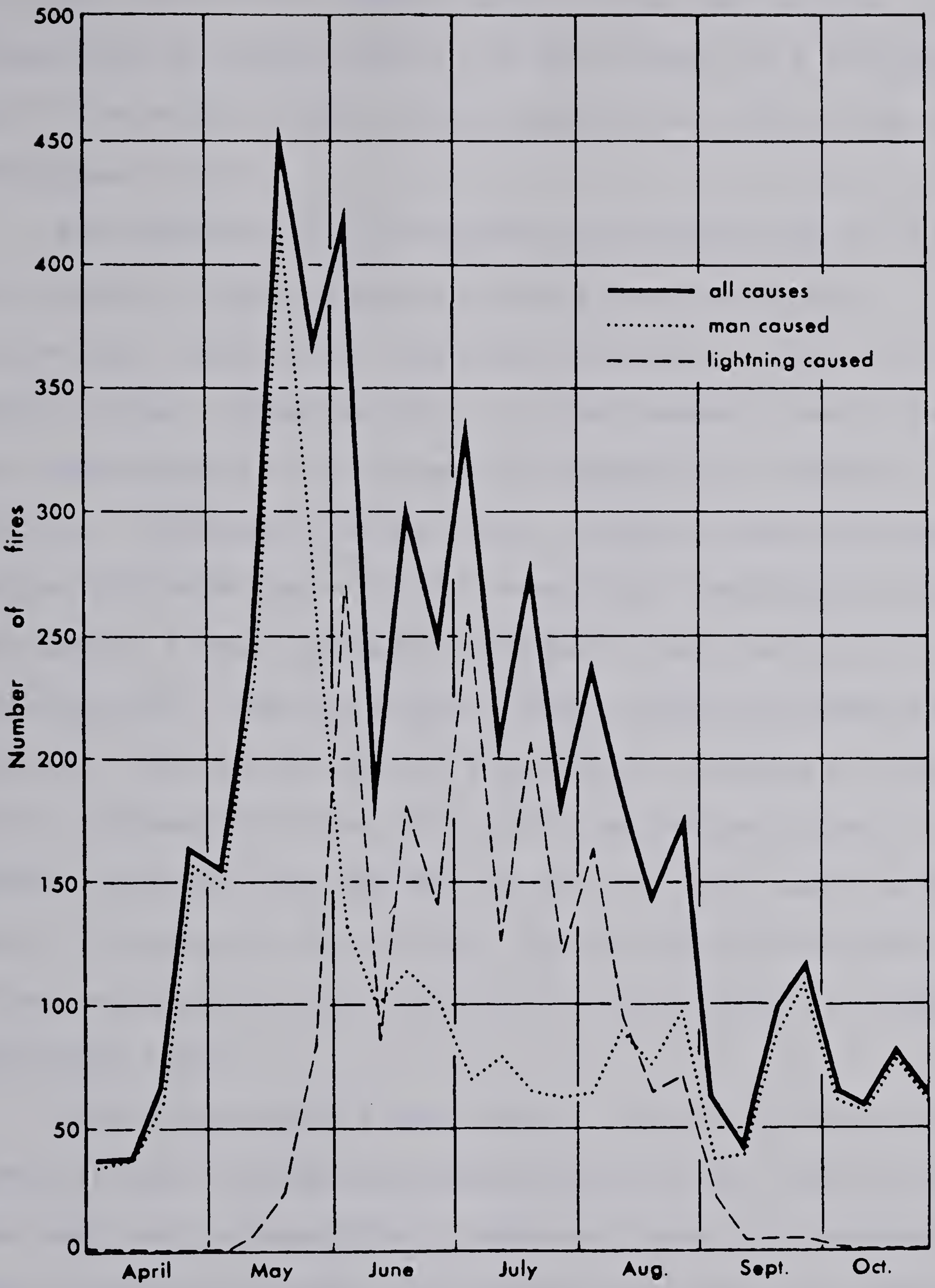
Within the commercial forests of Alberta a high degree of protection from fire is necessary to ensure continuation of forest yields. A common objective of fire control planning is to achieve maximum protection against fire losses while striving to hold presuppression, suppression and damage costs to a minimum. Planning in Alberta follows this rule. The Alberta Forest Service recognizes that its efforts to manage forest resources depend upon its ability to control fires.

Fire prevention is the optimal method of minimizing forest fire occurrence. Regulations concerning the use and control of fire are well defined in the Forest and Prairie Protection Act (Government of Alberta 1971). For example, land clearing and debris disposal by burning is closely monitored and can only be done with a fire permit based on inspection. Education and public awareness programs further enhance fire prevention efforts in Alberta. Nevertheless despite regulations and good intentions wildfires continue

to occur as a result of both carelessness and natural causes.

Although much remains to be learned about the seasonal variation of forest fire occurrence, it is generally understood that in the spring of the year, often while the frost is still in the ground, the ratio of cured to green forest fuels is greatest. Fuel moisture may be at its minimum and drying winds and lengthening periods of daylight increase the hazard created by the overwinter accumulation of dry grasses, needles and twigs.

As the growing season progresses many of these fuels become less flammable as sap begins to flow and as new leaves and grasses emerge. Temporal and spatial variations in humidity and precipitation have a major effect on fuel moisture as the fires season advances. Risk, or ignition potential, seems to vary as well as the fire season progresses. For example, during the months of April and May, between 1961 and 1970, almost all fires were man-caused, possibly because of a combination of high to extreme fire hazard and high ignition potential from spring burning and land clearing programs as well as careless use of fire, and incendiarism (Figure 2). From June through mid-August lightning causes the greatest number of fire starts. Following mid-August, the April-May trend prevails once more, as lightning incidence declines and man again becomes the primary causal agent (Miyagawa 1974). On a monthly basis more than a third of man-caused fires occurred in May while



Source: *Alberta, Energy and Natural Resources, Forest Service.*

Fig. 2. Provincial Total 1961-1970 Fire Incidence, Weekly Periods.

June was the second highest month. These two months accounted for almost 50% of the man-caused fire incidence while the month of May alone accounted for 94% of the damage (Miyagawa 1976).

Man-caused fires in Alberta are categorized as follows: (a) forest or wood industry fires (forest products extraction industries), (b) other industry fires (oil, gas, mining, power companies etc.) (c) settlement (land clearing and improvement), (d) recreation (campfires, smokers, hunters, fishermen) (e) railroad (right-of-way clearing, engine and brake sparks) (f) incendiary (deliberately set, non-permit fires) (g) public project (road, airstrip construction), and (h) miscellaneous known (children with matches, vehicle and aircraft accidents, trappers) (Miyagawa 1976). Between 1961 and 1975, 5271 man-caused fires in Alberta damaged over 406,800 ha and involved suppression costs in excess of $8 million. During this period man-caused fires amounted to almost 60% of the total from all causes (Miyagawa 1976).

Lightning-caused fires account for the balance of forest fires. Unlike man-caused forest fires, which are for the most part preventable, lightning fires are dependent upon prevailing weather and hazard conditions and cannot be prevented in the same sense of the word. Whereas man-caused incidence peaks by the third week of May and falls rapidly to a fairly constant level by the middle of June, lightning fire incidence peaks in the first week of June and first

week in July before falling off by the middle of August (Figure 2) (Miyagawa 1974).

Man-caused fires generally occur in areas of human activity, largely restricted to forest fringe zones and forest access routes, while lightning fires occur in a more dispersed manner often in remote regions of the province. They sometimes lead to multiple occurrence situations which seriously stress the initial attack capability of the suppression organization and, if hazardous conditions prevail, costly "problem" fires can result. These fires which exceed 200 ha are known as "E" class fires. Of a total of 3519 fires between 1970 and 1974, 90 (2.5%) such fires, some of which occurred during high lightning incidence periods, accounted for 92% of the total area destroyed by fire and 57% of the fire suppression funds expended during that period (Miyagawa 1975).

Information such as this suggests that there is a critical need to have on hand a fire suppression resource capability, optimally located, which is qualified to take early and decisive action against fire starts, under even the most hazardous of burning conditions, in order to limit the number of fires causing extensive and costly damage.

Fire danger forecasting and rating

Forest fuels vary in size from fine (twigs, branches, grasses, mosses, etc.) to heavy (logs, deep duff, standing trees etc.). These physical properties of forest fuels in turn affect their response to drying conditions. It is

generally recognized that there are four important weather variables which influence drying of these fuels. These are: ambient temperature, wind velocity, relative humidity, and precipitation. In order to predict the interaction of these parameters on fuel flammability, and subsequently fire hazard, the Canadian Fire Weather Index tables have been developed (Environment Canada 1978). There are six components of the Forest Fire Weather Index which provide a numerical rating of relative wildland fire potential. The first three components, fine fuel moisture, duff moisture and drought provide the basis for fuel moisture codes. These codes respond to daily changes in the moisture contents of three classes of forest fuel, cured fine, loose organic, and heavy fuels. This is because each class exhibits a different drying rate which influences ease of ignition, fuel flammability, and support of combustion respectively. The remaining three components, initial spread index (ISI), buildup index (BUI), and fire weather index (FWI) are the respective fire behavior indices representing rate of spread, amount of available fuel and calculated fire intensity. The entire system is based solely upon weather parameters and does not take into account differences in liklihood or source of ignition, fuel arrangement, or topography (Van Wagner 1974). The end product is a comprehensive rating procedure which provides a uniform method of determining weather influences on burning conditions anywhere in Canada. The descriptive danger

classes and severity ranges, calibrated for the three fire behaviour indices in Alberta, are presented in Appendix 1 (Kiil et al. 1977).

A logical extension of the use of the Canadian Fire Weather Index is its application in the form of a fire danger index which is a numerical rating of fire danger factors affecting ignition, spread, control difficulty, and damage caused by forest fires. Such an index enables a forest protection agency to assess day-to-day preparedness and suppression requirements relative to the anticipated fire load, that is, the number and magnitude of fires requiring suppression action during a given period, within a specified area (Lawson 1977).

The AFS has its own fire weather unit originally set up in 1962 to respond to a growing need to gather, analyze and utilize weather information in the presuppression and suppression phases of the fire control program. Since 1969, this unit has become unique among all of the fire control organizations in Canada in that it has a permanent and seasonal staff of professional meteorologists as well as support technicians offering regular forecasts, local and spot forecasts, and weather briefings at headquarters and field offices alike (McDonald 1977). Continental and national weather information is assembled and analyzed along with lookout and ranger station weather reports. This information provides the fire control officer and the man on the fireline with up-to-date weather statistics and

forecasts in order that each may be better prepared to deal with the important influences of weather on fire hazard prediction and behavior potential.

Fire detection

The fire detection program in Alberta is dependent primarily upon the network of 141 fixed lookouts strategically located throughout the ten forests. Intermittent aerial and road patrols are carried out to supplement the fixed detection system, depending upon the regional severity of the fire hazard. The passage of thunderstorms calls for increased awareness in the areas where storm paths have been monitored. Additional aerial and infrared scanning patrols are routed through the regions where storms and lightning activity have been reported. The lookouts are expected to be extra alert under these conditions since they are the primary means of identifying storm paths as well as the location and number of lightning strikes. Supplementary to their role in fire detection these lookouts serve as weather station sites where daily measurements of rainfall, humidity, temperature and wind are recorded for later use in fire hazard rating. Their role in providing emergency or supplementary radio communications links is important as well.

Fire suppression priorities

In an effort to maximize the effectiveness of their fire control effort, the AFS has initiated a schedule of fire suppression priorities. In 1976, the location and

extent of resource values throughout the forest region of Alberta were identified. These included population centres, present land uses, and forest land based resources, such as timber, grazing, and water (McDonald 1976).

As a result, all land uses and values were compiled on an equal basis and no attempt was made to segregate them in monetary terms. The composite fire suppression priorities map which evolved was formulated on the basis of the threat of wildfire to human life, real property and multiple resource values, watershed, recreation, oil and gas activities, timber, and grazing in that order. Figure 3 depicts this resultant priorities schedule wherein priorities have been assigned using the following criteria (McDonald 1976):

No. 1 priority: population areas to a minimum area of one township.

No. 2 priority: major watershed and recreation areas including merchantable coniferous timber volumes (> 7400 fbm/ha).

No. 3 priority: active oil and gas fields and timber management units containing merchantable coniferous timber volumes (> 7400 fbm/ha).

No. 4 priority: important grazing areas and potentially productive or low volume timber management units (< 7400 fbm/ha).

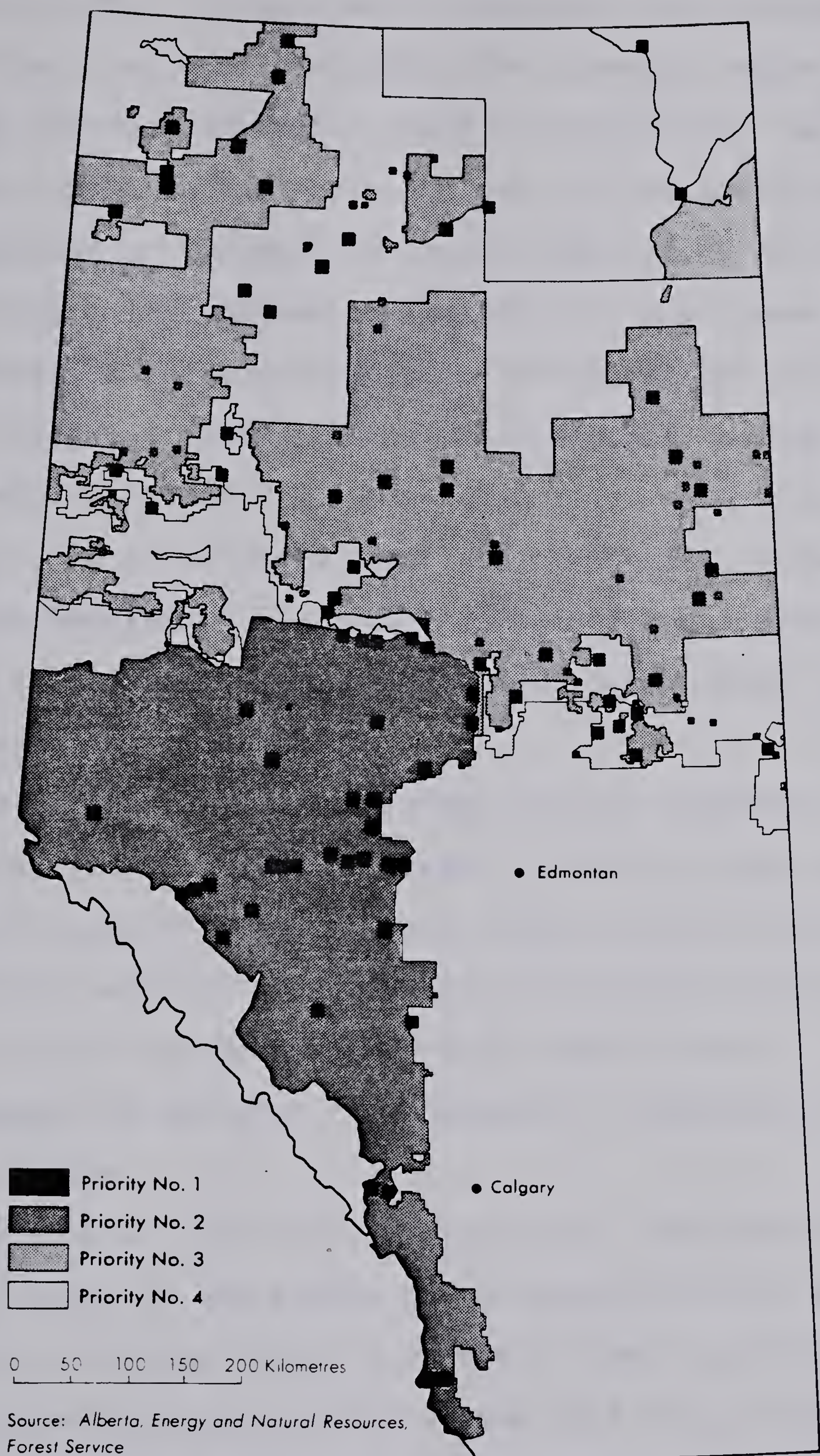


Fig. 3. Alberta Fire Suppression Priorities.

At a glance, it is readily apparent that the many communities scattered throughout the forested region are afforded the most intensive level of protection. The large forested region to the north and west of the agricultural zone, bounded on the west by the national parks and to the north along a line between Grande Prairie and Lesser Slave Lake, receives the next highest priority rating. This is because of the extensive forest industry, oil and gas, and other natural resource benefits associated with this area, a large portion of which is comprised of the east slopes of the Rocky Mountains. The northern half of the province is generally rated priority three or four owing primarily to differences in timber values.

Having identified, and rated relative resource "values-at-risk" within the forest protection area; and, armed with some of the most up-to-date and qualified fire suppression capabilities in Canada, the Alberta Forest Service is well prepared to priorize suppression requirements as and when fire hazards or outbreaks warrant.

Initial Attack

The Glossary of Forest Fire Control Terms defines initial attack as the action taken to control a fire by the first fire fighting force to arrive at the fire (CCFFC 1976). Brown and Davis (1973) stress that the strength of attack is almost as important as the speed of attack in the initial stages of fire control. Here the speed of attack means nothing unless coupled with the capability to stop the

spread of a fire or slow or stop the combustion process on small fires.

Highly trained, mobile crews with mechanized equipment can generally provide the capability to successfully control a forest fire in its early stages of growth. This effort can be exhibited on land and in the air depending on the transport mode utilized. Trucks, all-terrain vehicles, fixed-wing aircraft and helicopters all offer unique advantages under varying conditions. Where speed and "hitting-power" are considered to be fundamental requirements, the aerial tanker must be given serious consideration as well. The airtanker, as a mode of transport, has the capacity to deliver from 1000 to 12000 litres of fire fighting liquid quickly and efficiently to any fire within its striking range regardless of accessibility or topography. When the on-board delivery system is compartmented, several combinations of attack capability can be exhibited. Airtankers are generally categorized according to their capacity to carry chemical fire retardants, water or thickened water from land bases or in an amphibious mode. They range in size and payload capacity in accordance with their original design limits. Almost all of those in use today were initially designed and built for some other purpose, generally military or commercial. Only one has been developed specifically for fire fighting purposes, that is the Canadair CL-215 amphibious water-scooper.

The airtanker program in Alberta has undergone some significant changes during the past twenty years or so. Since a Grumman TBM Avenger was first flown off the Jasper Park airstrip with a load of water at a critical stage during the 1956 fire season, the AFS has kept pace with technological advances in aerial fire suppression. In 1959 the first chemical fire retardants were dropped from Stearman biplanes. During the 1960's the Snow and Thrush Commanders were used extensively and chemical retardant planes and tanker bases were upgraded. Late in this period the amphibious PBY-5A Canso was introduced and it has played an important role in attacking fires, large and small, since that time. Early in the 1970's the fleet of smaller tankers was disbanded as more emphasis was being placed on larger, faster, harder hitting tankers such as the Douglas B-26, a former late WW II and Korean War fighter bomber. Since 1974 two groups of two or three B-26's and two groups of Cansos have been under contract. These aircraft form the nucleus of Alberta's aerial initial attack program, although several helicopters are brought into the program annually to fulfill aerial attack requirements. Each bomber group has its own affiliated lead plane or "bird-dog" aircraft which carries the "bird-dog officer" who is the AFS representative in charge of air attack operations over a fire.

The B-26's are limited to land-based operations and carry 3650 litres of chemical fire retardant each trip; whereas the Cansos are amphibious and can be initially

dispatched with 3200 litres of retardant. They can subsequently be self-loaded with 3800 litres of water through a loading probe while skimming over the surface of a lake. A coloured water-thickening powder can be added during this process to produce a reddish coloured viscous water solution when completely hydrated. This thickened water is capable of resisting evaporation and drift during the descent phase when the load is released from the aircraft tank. These bomber groups can often take action on a fire within one-half hour of it being spotted, and may continue such action until adequate ground suppression crews arrive at the scene to complete the task of extinguishing and "mopping-up" the fire. Performance characteristics of the above airtankers are presented in Appendix 2.

Alberta's airtanker contracts are in effect from mid-May to mid-August annually. Depending upon fire hazard and risk conditions, however, these contracts may be extended at either end of this period. As a general rule the four groups are assigned among the north-central Forests during the early part of the contract. Fire hazard and ignition potential is often higher in these Forests at that time of year because of the interface between forest and agricultural lands where land clearing and debris burning activities can present problems. In addition there are localized regions of high-to-extreme hazard where specific fuel, relief, or risk conditions (e.g. Swan Hills, Marten Hills) are also of concern. As the summer progresses, dryer

conditions along the east slopes occur at higher elevations and one or two groups of B-26's will generally be sent to the foothill Forests. By this time lightning is the primary casual agent throughout the province and the periodic assignment of tanker groups can readily be adjusted to account for local or regional storm activity anywhere in the province.

Several regions within Alberta have been designated as having sufficient water bodies to support continuous Canso skimming operations. The major extent of these zones involves a large area to the north of Lesser Slave Lake, two areas along the east side of the province around Lac La Biche and north of Fort McMurray, and two smaller areas along the 60th parallel of latitude west of Wood Buffalo National Park. On the other hand, the Canso is not well suited to fire bombing in the east slopes region because of the limited number of suitable lakes and the mountainous flying conditions. The B-26 groups and helicopter supported ground crews are generally responsible for initial attack in this high value region of Alberta.

There are currently eleven permanent airtanker bases in Alberta one in each Forest with the exception of the Bow-Crow Forest where there are two. Further discussion of the 1974 base network is presented in Chapter 3. Each of these bases is located at the airport which serves the community and forest service requirements at the ten Forest headquarters centres. An additional base has been

constructed at Pincher Creek in the Bow-Crow Forest because of the high resource values and mountainous terrain in the extreme southwestern corner of the province. Each base has a chemical fire retardant mixing facility and affiliated storage and loading capabilities. Accommodation, communication and recreation facilities are also provided at each base for the pilots and base operation crews stationed there.

II. LITERATURE REVIEW

One of the most significant technological developments in forest fire suppression in recent years has been the introduction of aerial tankers, or fire bombers. Since the inception of some rather crude aerial water bombing practices in 1931, several stages of airtanker development have been witnessed (Reinecher and Phillips 1960). Following the end of World War II surplus military aircraft such as the PBY Canso, the Boeing B-17 Flying Fortress, the Mitchell B-25, the Grumman TBM Avenger, the Consolidated PB4Y-2 Privateer, the Douglas B-26 and others were converted for fire bombing purposes. Some of the early experiments with these aircraft and the fire retardants they carried were abandoned for economic and safety reasons (Reinecher and Phillips 1960). Almost all of these early experiments were conducted in the U. S. A.

On the Canadian scene, because of the almost limitless availability of water, particularly in the Canadian Shield region, experiments centered on the development of water scooping and delivery systems using float equipped or amphibious aircraft. Much of this early work was conducted in Ontario with the De Havilland Beaver and Otter aircraft and the PBY-5A Canso. In the mid 1950's the N2S Stearman biplane, an agricultural spray plane, was converted to carry just over 450 litres of fire retardant (Ely et al. 1957). Other agricultural crop sprayers soon followed with the

conversion of the Snow and Thrush Commanders, the Grumman Super Ag-Cat and the Transland AG-2. In 1966 the Alberta Forest Service introduced the Snow and Thrush Commander airtankers and Gelgard-F fire retardant into its aerial suppression operations (Grigel 1970). The following year the first PBY-5A was contracted and by 1970 the B-26 Invader was fire bombing in Alberta.

Although the airtanker is a relatively recent fire control tool, it has been a popular subject of literary discussion. Simard and Young (1977) have prepared an extensive annotated bibliography which provides over 700 literature references covering all facets of the use of airtankers in fire control. In addition Martell (1977) has prepared a comprehensive draft bibliography of over 40 operations research studies in fire control including references to several aerial detection, aerial attack, and airtanker selection and performance models. The literature reviewed for this thesis, however, relates more specifically to airtanker allocation optimization studies and some of the operations research literature devoted to location - allocation models.

Maloney (1973) is generally credited with having developed the first airtanker allocation model. His was a cost-minimizing model of the California Division of Forestry (CDF) airtanker (retardant) delivery system as a subsystem of the overall CDF fire control program. This linear programming model minimized the total cost of retardant

delivery by four specific types of airtankers, delivering two specific retardants, from among twelve specific bases, subject to certain cost, airtanker productivity, time, and fire growth constraints. Maloney's model output defined an optimal airtanker allocation for any desired level of operation of the aerial attack program among all air attack bases under the jurisdiction of the CDF. In other words, subsystem costs would be minimized by allocating the most cost-effective types of airtanker to specific bases within geographical as well as cost constraints.

A somewhat similar mathematical model was developed by the Aerospace Corporation (1973) to determine, for a defined geographical region, a preferred pre-fire allocation of airtankers based on the lowest total expected damage plus operating costs. This aircraft deployment procedure used nonlinear optimization to minimize total fire containment costs for one or more fires, where cost was treated as a nonlinear function of the number of airtankers deployed.

Greulich and O'Regan (1975) developed superior aerial attack strategies dealing with dispatch considerations, daily burning index classes, protection priority regions and historical fire occurrence information. Their model then identified for a given budget level, the optimum allocation of five airtankers (two types) among three CDF air bases in northern California. A transfer rule assigned each aircraft to the optimal base on the basis of day-to-day burning index values.

Workers such as Martell (1971), Vesprini and Brady (1974) and Renton _et_ _al_. (1975) have also contributed to the development of cost minimizing initial attack models with particular emphasis being given to the airtanker allocation problem. All of the resource allocation models referenced thus far are based upon the singular premise that a given type, number, and capability of airtanker will be optimally allocated among all predetermined base locations within a defined geographic region. The one exception to this statement is a study by Simard and Forster (1971) which stressed the interdependence of airtankers and the combinations of airports to which they might be assigned. In Alberta, the problem stems from the need to determine the optimal locations of air attack bases (4) from among a greater number of such centres (11) so that a function relating protection priority and base-to-fire distances travelled is optimized, during one-strike initial attack missions. This type of problem has only recently received attention in the airtanker operations research literature by Hodgson and Newstead (1978a) and (1978b). This thesis is devoted to further investigation of this problem.

The matter of serving a number of demand points and determining optimal facility locations falls within the general class of problems known as location-allocation problems. A brief discussion of these problems, the development of solution techniques, and their applicability to this undertaking will serve to introduce the subject and

bring some of the models into perspective.

Early in the twentieth century, Alfred Weber, a German economist, pioneered location theory in his consideration of industrial location relative to the location of two resources and a single market wherein transportation costs were to be minimized. More recently, a practical interpretation of the location-allocation problem has been described by Scott (1971) as being representative of a social or economic system which is identifiable as a set of flows between a number of central facilities and some set of geographically dispersed source or destination points. Following the Second World War, linear programming techniques and more recently tree-searching methods have contributed greatly to the solution of optimization problems to the point where today's electronic data processing capabilities have significantly aided and expanded location-allocation research.

Where the flow assignment is known but the geographical location of the facilities is unknown, then the problem is a purely locational one as in the classical Weberian case wherein the cost of all flows between the central facility and all other designated points in (discrete) space is minimized. Alternately, if the facility locations are known but the assignment flows are unknown, then the problem becomes the ordinary transportation problem of linear programming (Scott 1971). Location-allocation models provide the opportunity to solve both of these problems

simultaneously. For example L-A models can be applied to problems involving the location of plants with respect to their raw materials and markets, social service facilities such as clinics, hospitals and day-care centres with respect to their clients, emergency services such as fire, ambulance and police stations with respect to their service areas and so on. ReVelle (1968), for instance, was motivated by the problem of locating clinics for chronic disease care in his study of central facilities location on a network.

Within the context of the AFS air attack program there exists a location-allocation problem in dealing with the optimal placement of four groups of airtankers among eleven designated air attack bases scattered throughout the forested region of the province. This calls for a trade-off between minimization of base-to-fire distances and maximization of the level of protection afforded to the resource values under protection or "at risk". By contrast, the solution techniques employed to date by fire operations researchers have simply sought to place some level of airtanker capability at each and every base to provide a maximum level of protection or suppression capability while attempting to minimize costs.

Cooper (1963), an early and well-known investigator of L-A problems was the first to deal with location-allocation situations in continuous space. He developed a heuristic algorithm which alternately locates and allocates points on a plane to defined centroids. Through this iterative process

Cooper's algorithm seeks to solve for the optimal locations of the Cartesian co-ordinates (x,y pairs) of the designated centroids or median centres of the point set. This partitioning process is conducted in such a way that the total aggregate distance between all points on the plane and the centroids to which they are allocated, is minimized. Mathematically this problem can be expressed as:

$$\text{Minimize:} \qquad Z = \sum_{i=1}^{m} \sum_{j=1}^{n} \lambda ij \sqrt{(X*i - xj)^2 + (Y*i - yj)^2} \qquad (1)$$

$$\text{Subject to:} \quad \sum_{i=1}^{m} \lambda ij = 1 \qquad (j = 1, 2, \ldots, n) \qquad (2)$$

$$\lambda ij = \begin{cases} 1 & (i = 1, 2, \ldots, m) \\ 0 & (j = 1, 2, \ldots, n) \end{cases} \qquad (3)$$

where $X*i$ and $Y*i$ are the Cartesian co-ordinates of the i th centroid, and xj and yj are the co-ordinates of point j on the plane. The constraint (2) specifies that points on the plane be fully assigned; and the 0-1 decision variable λij specifies whether or not point j is assigned to centroid i.

The foregoing is a classical example of the L-A problem and is also known as the p-median problem, where the median is that point in space which minimizes the total aggregate distance between itself and all other points in the set on the plane. By way of an example, along a line a single median centre can serve as the optimal centroid or centre of gravity which minimizes the total aggregate distance to all other points on the line. In space, where two points jointly

serve to minimize total aggregate distance, this is known as the 2-median problem. Similarly, if "p" points satisfy this objective then this becomes a p-median problem.

In many instances the point set involves some element of weighting where each point on the plane has some measure attached to it. This presents a weighted p-median problem. For example, it may be desirable to determine the locations of a number of facilities, such as parks, in rural areas. In such a case the cities would comprise the demand centres and the objective would be to minimize the aggregate distance between the facilities and the city residents. Here, each city point would be weighted by its population and the optimal p-median would minimize the aggregate distance from all of the cities to the parks. Mathematically, this problem would be expressed as the minimization of:

$$Z = \sum_{i=1}^{m} \sum_{j=1}^{n} \lambda ij \; wj \quad \sqrt{(X*i - xj)^2 + (Y*i - yj)^2} \qquad (4)$$

where the term wj has been introduced to "weight" the travel distance.

Cooper's algorithm applies to problems set in continuous space and solves for the location of x, y co-ordinates which minimize the aggregate distance between a set or sets of points and their associated centroid(s). In some instances, however, this solution technique is inappropriate. One such case occurs where facilities must locate at certain designated points, as in the airtanker

problem. Here, aerial tanker base facilities must be located at airports where supplies and services can be provided in support of the aerial attack program. This presents a p-median problem set in discrete space because it involves the determination of "p" optimal locations from among a specified set of potential locations.

ReVelle (1968) developed a linear programme to solve the p-median problem in discrete space. His objective was to minimize the sum of population-distance or population-time interaction; and he has been credited with proving the problem to be structured as a 0-1 linear programming problem with facilities restricted to nodes of the network. In further development of ReVelle's linear programme, ReVelle and Swain (1970) showed that a linear programming format would always yield a 0-1 optimum solution although in some cases non-binary alternative optima may result.

This linear programming formulation seeks to

$$\text{Minimize:} \quad Z = \sum_{i=1}^{n} \sum_{j=1}^{n} ai.dij.xij \tag{5}$$

$$\text{Subject to:} \quad \sum_{j=1}^{n} xij = 1 \qquad (i = 1, 2, \text{----}, n) \tag{6}$$

$$xjj \geq xij \qquad \begin{matrix}(i = 1, 2, \text{----}, n) \\ (j = 1, 2, \text{----}, n) \\ (i \neq j)\end{matrix} \tag{7}$$

$$\sum_{i=1}^{n} xii = p \tag{8}$$

$$xij \geq 0 \qquad \begin{matrix}(i = 1, 2, \ldots, n) \\ (j = 1, 2, \ldots, n)\end{matrix} \tag{9}$$

Where: n = number of communities

p = number of centres to which communities are to be assigned, i.e. central facilities

a_i = population of the ith community, $i = 1, 2, \ldots, n$

d_{ij} = shortest distance from community i to community j

x_{ij} = decision variable, 1 if community i does assign to community j, 0 if not

Three types of constraints are required to ensure that each community be fully assigned (6); to restrict assignments to only those communities which assign to themselves, i.e. those which have facilities (7); and to fix the number of central facilities and thus the number of facilities which might assign to themselves (8). A typical non-negativity constraint (9) is also provided. The ReVelle and Swain (1970) formulation thus enabled optimization of facility locations in discrete space such that one or more of the communities designated for service could also act as central facility locations.

The p-median solution insists that all points be served by minimizing the aggregate distance between all demand points and the nearest centroids. However, in some cases this may be inappropriate because of capacity limitations or maximum service ranges. For instance, there may be a need to locate facilities in such a way that they be readily accessible to their clientele, or where travel restrictions dictate a maximum range of effective service. Such might be the case with civil administration or social service

facilities.

There are two L-A approaches to solving problems involving maximum ranges of service. In the first instance, it is possible to maximize the level of coverage provided by the facilities so that as much demand as possible is brought into range or served within a specified maximum service distance. In the second case as reported by Holmes et al. (1972), maximum coverage could be traded off with the minimization of distance where the level of service may decline or become less desireable with increasing distance, to a predefined maximum.

In other words maximum service may be determined by maximizing:

$$Z = \sum_{i=1}^{m} \sum_{j=1}^{n} wj.xij \qquad (10)$$

or, as in the Holmes model, service maximization and distance minimization may be traded off by maximizing:

$$Z = \sum_{i=1}^{m} \sum_{j=1}^{n} wj\ (S - dij)\ xij \qquad (11)$$

Where S is the maximum range of service.

The maximum coverage model implicity assumes that in the case of the forest fire problem, all fire occurrences would be equally well served if occurring within the maximum range of airtanker effectiveness. This approach, however,

does not consider that airtanker effectiveness declines with increasing distance between the base and the target. Based on the latter premise, Hodgson and Newstead (1978a) employed a modification of the Holmes et al. (1972) model to optimally locate four air attack bases among the eleven such bases in Alberta during three specified fire occurrence periods.

The Hodgson and Newstead (1978a) model trades off the importance of maximizing the weight or "value-at-risk" served within the attack range of a base with the minimization of the average base-to-fire distance, on the assumption that there is a linear decay in airtanker effectiveness with increasing distance, to zero effectiveness at S = 193 km.

The objective function maximizes:

$$Z = \sum_{i=1}^{m}\sum_{j=1}^{n} vj\ (S - dij)xij \tag{12}$$

Subject to:

$$\sum_{i=1}^{m} xij \leq 1 \qquad (i = 1, 2, \ldots, n) \tag{13}$$

$$xii - xij \geq 0 \qquad \begin{matrix}(i = 1, 2, \ldots, m)\\(j = 1, 2, \ldots, n)\end{matrix} \tag{14}$$

$$\sum_{i=1}^{m} xii = p \tag{15}$$

$$xij = \begin{cases}1 & (i = 1, 2, \ldots, m)\\0 & (j = 1, 2, \ldots, n)\end{cases} \tag{16}$$

Where: m = number of potential air attack bases

n = number of fire targets including air bases

p = number of air bases to be designated as optimal attack bases

v_j = weight (value - at - risk) at target j

d_{ij} = airline distance, air base i to target j

x_{ij} = decision variable, 1 if target is assigned, 0 if not

S = designated maximum range of service

Linear programming was originally employed to solve the preceding model, however, computation time proved to be quite costly owing to the large number of variables and constraints encountered. As a result, the same problem was reconsidered by Hodgson and Newstead (1978b) using a heuristic solution procedure applied to a combinatorial formulation of the algorithm.

Thus formulated, the model selects a set of facilities Λ so as to maximize:

$$Z = \sum_{i=1}^{m} \sum_{j=1}^{n} v_j \, (S - d_{ij}) \, \lambda_{ij} \qquad (17)$$

Subject to: $$|\Lambda| = p \qquad (18)$$

such that exactly p of the potential air attack bases become members of the set of attack bases

$$\lambda_{ij} = \begin{cases} 1 \text{ if } d_{ij} = \min\limits_{i \in \Lambda} d_{ij}, \ d_{ij} < S \\ 0 \text{ otherwise} \end{cases} \quad \begin{matrix} (i = 1, 2, \ldots, m) \\ (j = 1, 2, \ldots, n) \end{matrix} \qquad (19)$$

Heuristic algorithms, although not able to guarantee global optima, offer very real cost savings and determinations of excellent quality despite the possibility of generating suboptional solutions. To solve the preceding model Hodgson and Newstead (1978b) employed a variant of the Teitz and Bart (1968) vertex substitution method in order to compare computation costs and solution quality with the previously referenced linear programming routine. During one particular fire occurrence period investigated, the heuristic algorithm performed very well in relation to the linear programming results. When processing time and costs were compared, the heuristic solution resulted in savings of over $50.00 for the single computer run ($0.34 versus $54.00). In only one case was the heuristic solution lower than the true optimum, and that marginally. In addition, there are cases when the Holmes et al. (1972) linear programming approach can produce non-binary, and thus meaningless, optima. According to ReVelle and Swain (1970) these optima occur when demand points are equidistant from service centres, resulting in fractional values of the decision variable.

In summary, Hodgson and Newstead (1978a) noted that heuristic programming offered adequate efficiency and accuracy to warrant application to location - allocation problems dealing with the location of airtankers. This observation is generally supported by workers such as Kohler and Rushton (1973) and Lea (1973) who found heuristic

solutions to be "highly reliable" and "usually of high quality" even in the case of sub-optimal solutions.

This thesis, as will be discussed in detail in the next chapter, employs a modified version of the Hodgson and Newstead (1978b) distance-biased maximum coverage model because of the authors' conclusions that this model offers superiority in providing a high degree of "value-at-risk" coverage as well as incorporating a distance - effectiveness function. Such a function is of prime importance in forest fire control problems because elapsed time or strike distance can have a significant bearing on fire size at initial attack.

III. THE MODEL - DEFINITION, VARIABLES, AND ASSUMPTIONS

A common planning problem is to locate a limited number of central facilities in order to maximize services to an existing population. This problem has been introduced and discussed at some length in the preceding chapter. In the case of the AFS air attack program, it would be beneficial to the forest protection headquarters to know in advance where the four bomber groups could be best positioned among the eleven attack bases in anticipation of fire outbreaks throughout the province. Since it is not possible to predict the exact locations of fire starts to generate model input, this thesis follows the procedure of previous fire researchers and takes a retrospective viewpoint and uses fire location records for a given fire season (1974). This procedure allows the assessment of the model's performance and applicability to this type of problem in the event that improved fire occurrence predictions become available and real-time modelling becomes feasible in forest fire control situations.

It is important in wildfire control to initiate attack and suppression proceedings as quickly and efficiently as possible in order to capitalize on control opportunities available, particularly as the fire hazard and value of threatened resources increases. Fire behavior is dependent upon fuels, weather, and topography, while the element of time influences the rate of fire growth. The airtanker

offers the potential to minimize this time element or duration of fire growth, once a fire has been reported to a nearby attack base, owing to the relatively short mobilization, dispatch and travel times involved. Once over the fire, the combined capability of the number of tankers dispatched, ground crew support, and fire behavior circumstances will largely determine the level of effectiveness of the mission.

The model employed in this thesis is an extension of that reported by Hodgson and Newstead (1978a,b), modified in such a way that airtanker strike distance (time) and fire hazard (growth potential) are given more consideration because of the manner in which they might influence mission success. Accordingly, as fire severity (FWI) increases, the maximum attack range is reduced. These features of the model and the relevant data set will be discussed following presentation of the model.

A. The Model

This model, as noted earlier, trades off the importance of serving as much value-at-risk as possible with the importance of locating the four bomber groups as close as possible to the fire ocurrences dealt with. It seeks a set, Λ, of p attack bases which maximizes the function:

$$Z = \sum_{i=1}^{m} \sum_{j=1}^{n} vj \ (Sj - dij) \ \lambda ij \qquad (20)$$

Subject to the same constraints (18) and (19) as outlined in the previous chapter.

This function is exactly the same as that employed by Hodgson and Newstead (1978b) but in this case it allows the use of a variable attack range, Sj, which is defined according to the prevailing fire hazard (FWI) category at fire location j. In this sense, if the data and knowledge were available it is conceivable that a particular attack range could be inserted into the model for each fire site considered. Here Sj is taken to fall into one of three categories which will be discussed in the next section.

B. Determination of Model Variables

Potential Air Attack Bases - m:

Currently airtanker bases in Alberta are located almost exclusively at the administrative centre of each Forest. The one exception is Pincher Creek, where a recently constructed base supplements the Bow-Crow Forest headquarters base in Calgary. In 1974 there were two exceptions to the rule when Fox Creek and Lethbridge served as base locations in the Whitecourt and Bow-Crow Forests respectively. Since 1974 a new base has been established at the Whitecourt airport and the Lethbridge base has been moved to Pincher Creek. In all other instances suitable airport facilities and runway requirements were already established at the Forest headquarters community and permanent airtanker bases were sited accordingly. (Appendix 3).

Candidate Fires - n:

Following the procedure employed by earlier researchers in this field [Maloney (1973), Greulich and O'Regan (1975), and Hodgson and Newstead (1978 a,b)], this thesis utilizes historical fire occurrence data specifically those recorded for a given fire season. The year 1974 was selected for two reasons: (1) it was the first full fire season in which the present four groups of airtankers were under contract (two groups of three B-26 airtankers and two groups of two PBY-5A Cansos); and (2) it was a relatively active fire season from the standpoint of the aerial attack program, particularly when compared with the years 1973 and 1975 for which similar data were available. The years 1976 and 1977 were not considered because of a lack of computerized fire report summaries at the time that this thesis was started and because of the lower level of air attack activity when compared with 1974.

In order to compare model results with the actual locational circumstances which prevailed during the 1974 fire season, it was necessary that common time frames apply to each. It was decided that the 1974 airtanker base assignment roster would best serve these temporal requirements and accordingly, all model runs are based on the 23 specific time periods for which the base locations of each group were known (Appendix 4).

The Alberta Forest Service individual fire report form is used to document extensive information pertaining to each

forest fire attacked anywhere in the province. Following a transcoding procedure, this information is reduced to simple numeric and alphabetic codes and recorded on magnetic computer tapes (Appendix 5). These tapes have been made available to the author for research purposes through a memorandum of agreement between the Northern Forest Research Centre and the Alberta Forest Service. All fire location, hazard, time and distance parameters involved in the data screening process have been selected from these tapes. Additional sources of information such as seasonal statistics and trends and airtanker activity summaries will also be referred to periodically in the data assembly portion of this thesis.

During any given fire season it is virtually impossible for airtankers to take action on all fires throughout a province the size of Alberta, nor would it be economically feasible to consider doing so. Therefore, for the purpose of selecting historical fire starts which were eligible to receive tanker action, it was necessary to derive simple dispatching rules whereby a "reasonable" number of fires could be considered as likely airtanker "candidate" fires.

Several criteria were arbitrarily selected as operationally feasible airtanker dispatch guidelines for screening candidate fires. These were based upon personal knowledge and experience of the author and communication with aircraft dispatch officers at the AFS. Factors such as duration of airtanker contract, fire size at initial attack,

prevailing fire hazard, and the availability of alternate attack resources were considered in developing the following list of rejection criteria.

Actual fires were withheld from the list of potential or candidate airtanker fires if:

1. The fire occurred prior to May 15, 1974, the initiation of the airtanker contract period.
2. The fire occurred after August 15, 1974, the termination of the airtanker contract period.
3. The fire was greater than 4.05 ha at initial attack, beyond which size aerial attack would likely be ineffective in achieving some measure of control on a "one-strike" basis.
4. The FWI = 1 which suggests that airtanker action would have been unnecessary or in excess of suppression requirements.
5. The getaway to attack time by alternate resources was ≤ 0.5 hr and $2 \leq \text{FWI} \leq 8$ on the assumption that supplementary aerial attack resources would have offered little or no significant control advantages under these low to moderate hazard conditions.
6. The getaway to attack time by alternate resources was ≤ 0.2 hr and $8 < \text{FWI} \leq 25$ on the assumption that supplementary aerial attack resources would have offered little or no significant control advantages despite these high to very high hazard conditions.

This procedure resulted in the selection of only those fires deemed likely to have benefited from one-strike initial attack by airtankers. It was assumed that fires occurring when the FWI exceeded 25 (extreme hazard) would receive immediate "all out" aerial and ground attack. As a result of this process 271 fires were rejected for one reason, 61 for 2 reasons and 18 for 3 reasons, to a total of 350 rejections. The remaining 248 fires accounted for 41% of the actual number occurring during the 1974 fire season.

Value at risk - vj:

This term is introduced by way of definition of the recently developed AFS fire suppression priority schedule. This priority rating recognizes the potentially detrimental impact that wildfire can have on human life, real property, multiple resource values, watersheds, recreation, oil and gas facilities, timber resources and grazing in that order and as presented earlier in this study (McDonald 1976). The four resultant priority ratings have been reversed to provide estimates of value-at-risk. For example, fires occurring in priority zone one have been assigned a value-at-risk of four units. Precise values would have been more desirable, however, in their absence the surrogate measures adopted do reflect current AFS fire control decision-making criteria. The geographic location of each fire was subsequently identified on a fire suppression priorities map to determine its value-at-risk.

Base-to-fire distance - dij:

This variable is represented by the great circle or airline distance between each candidate fire and the airtanker base to which it is to be allocated. Since the location of each fire origin is recorded by the AFS in terms of its legal description (legal subdivision, section, township, range and meridian) all base and fire locations had to be redefined in terms of their geographic co-ordinates prior to determining point-to-point distances.

These data treatments were accomplished in two stages. Initially a computerized map transformation routine was used to transform the legal fire location description based upon the Dominion Land Survey (DLS) directly to geographic co-ordinates. By this process the original fire location information, recorded to the nearest legal subdivision, on the fire report summary tapes was converted to latitude and longtitude. Subsequently, another subroutine was used to calculate the great circle distance between the geographic co-ordinates of any two points for all fire and base locations.[1]

Maximum attack range - S_j:

The maximum attack ranges of the airtanker groups, as employed in this model have been defined to reflect the assumed influence of increasing base-to-fire distance on declining airtanker effectiveness.

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[1]The initial transformation routine was originally made available by the U. of A. Department of Geology and modified by the U. of A. Computing Services and stored in the file NEW: PROJECTION. The point-to-point distance calculations were accomplished with a great circle distance sub-routine provided by M. J. Hodgson, U. of A. Department of Geography.

On the basis of an unrefined distance decay function the following three attack ranges, Sj, were arbitrarily selected by the author as reasonable first estimates of the effect of distance and fire hazard on the effectiveness of airtankers operating according to a one-strike concept:

Sj = 30 km if $\quad FWI > 25$

Sj = 65 km if $\quad 8 < FWI \leq 25$

Sj = 200 km if $\quad 2 \leq FWI \leq 8$

The Fire Weather Index (FWI) was chosen as an indicator of the "likelihood" of successful one-strike aerial attack because it was the most meaningful relative measure of expected fire behavior readily available on magnetic tape, for each fire reported. The selection of three attack range categories stems from a desire to improve upon the 193 km maximum range reported in Hodgson and Newstead (1978 a,b) which in turn was taken from McDonald (1976) to be a reasonable outside limit of effectiveness for airtanker groups in Alberta.

It is conceivable that a non-linear decay function would be more realistic and better portray the expected decline in airtanker effectiveness with increasing distance, however, at the time of this investigation such data were not available. The term Sj-dij because of its linearity, implies full airtanker effectiveness at zero base-to-target distance and zero effectiveness at or beyond the maximum range for each FWI category considered. This is a recognized weakness in the present model and as a result work is

underway at the Northern Forest Research Centre to analyze this function in more detail. Fire specific aerial observer reports have been designed specifically to gather operational information which will enable assessment of airtanker effectiveness on actual attack missions.

<u>Airtanker performance and productivity assumptions</u>

Although the airtanker is a most versatile fire control tool owing to its speed, manoeuverability, and strike capacity, it is also a complex instrument. This has resulted in the need to make several simplifying assumptions concerning performance, within the context of the model.

First it is assumed that a one-strike concept applies wherein sufficient strike capacity is provided by a single airtanker group to effectively curtail fire spread until control is achieved.

Secondly, all groups are assumed to be dispatched from specified air attack bases with each airtanker carrying a full legal load of chemical fire retardant. Reloads and water pick-up potential are not considered. In fact, the two types of airtanker, the B-26 and PBY-5A Canso are considered equal in every respect even though they actually differ significantly in their respective roles and productive capacities (Appendix 2). Therefore, throughout this presentation the assumption holds that a "group" of three B-26's is equally as effective as a "group" of two Canso's so that amalgamated resource units may be considered.

As previously stated, great circle or airline distance

is used to describe the flight paths between any air attack base and fire site. In so doing airtanker performance is assumed to be unaffected by mechanical, topographic, weather, or fire related conditions. Allowances are not made to account for increased distances (time) incurred in take-off, over-fire, or landing requirements.

It is further assumed that the air attack strategy would incorporate either direct or indirect retardant application such that a fire would be rendered controllable by ground crews assumed to be at the site or expected shortly. Additional assumptions pertaining to airtanker performance provide for 100% drop accuracy and unconditional retardant effectiveness.

Somewhat similar assumptions have been introduced by other authors to deal with operational variables for which quantitative measures were not available. For example: Greulich and O'Regan (1975) defined their initial attack period as one hour, beginning with the dispatch of the first airtanker. This model assumes that a single strike by an airtanker group constitutes initial aerial attack. The Greulich and O'Regan model assigns each aircraft to a tanker base on the basis of observed burning index values while the model under discussion utilizes fire weather indices (FWI) to determine the likelihood of airtanker action on a given fire as well as the range of attack. These considerations have been discussed in the foregoing section on candidate fire selection procedures.

Maloney (1973) defined his "relevant fire set" as including all fires (1) that burned within defined land administration zones, (2) located within 15 minutes flight time of an air base, (3) beyond 15 minutes travel time of ground suppression forces, (4) which burned during the July 1, to October 15 fire season, and (5) which occurred during daylight hours only. He also derived mathematical functions to determine surrogate measures of airtanker efficiency where absolute values were not otherwise known.

Renton et al. (1975) assumed (1) that initial attack by air should occur within 15 minutes, (2) that a minimum of 3785 litres of retardant be delivered, (3) that the maximum fire size at control should not exceed 4.05 ha, and (4) that each forest area under protection be assigned a priority rank based upon watershed and residential development.

In summary, models simulating real-life circumstances suffer from inconsistencies and weaknesses readily apparent to managers of day-to-day activities. It has been shown in this chapter that this model is no different than any other in that its shortcomings may be attributed to several different limitations in the data base, the prevailing assumptions and the algorithm itself. However, as improved data become available, a concomitant reduction in the nature and extent of assumptions made by the modeller should serve to elevate the capability and credibility of simulation models in the eyes of the decision-makers.

IV. ANALYSIS OF OPTIMAL BASE LOCATIONS RESULTING FROM THE USE OF FIXED AND VARIABLE ATTACK RANGES

The development and application of location-allocation models have been considered in the preceding chapters, culminating with a presentation of the particular model employed in this study. The forest fire control problem herein deals with aerial attack resources which must be located in such a way that their service area is defined by one or more optimal attack radii. This is because at any given level of airtanker performance, capacity, and organizational grouping, potential effectiveness declines as the base-to-fire distance increases. This in turn can be attributed to the fact that fire resistance to control under certain fuel and weather conditions increases with time between discovery and initial attack. Although not considered in this study, multiple fire occurrence could also contribute to a reduction in overall aerial attack capability.

The purpose of this chapter is two-fold in its devotion to analysis of model results. Initially the output of two model runs will be compared and analyzed to demonstrate how the application of a fixed (200 km) attack range results in overestimation of the capabilities of four airtanker groups; and subsequently how the introduction of FWI dependent variable attack ranges yields superior locational results owing to the determination of more realistic base locations.

Secondly, the consequences of locational immobility of airtanker groups will be assessed by comparing the optimal base locations generated by the variable-range solution with those generated when these locations are held constant during the subsequent fire occurrence period.

A. Comparison of Results of Fixed and Variable Attack Ranges

The first model run was that governed by the fixed (200 km)-attack range (Sj). The general output for this solution is presented in Table 1 and includes a listing of the optimal base locations, the total value-at-risk and amount served, the total weighted distance (sum of value-at-risk x base-to-fire distance), the average base-to-fire distance per unit of value served, the total number of fires involved and served, and finally the computed value of the objective function for each time period considered. Similarly, the overall output for the variable attack range model is presented in Table 2.

Analysis of the results produced by these models will show the extent to which the first overestimates airtanker capabilities because of the number of fire targets considered to be within attack range but which in more realistic terms could not be effectively controlled by an airtanker group owing to their hazard rating and distance from base. This effect is examined by submitting the 200 km model locational output along with the prevailing base-to-fire distance (hazard) and value-at-risk ratings to

Table 1 Optimal Fixed-Range Solution

Time Period	Airtanker Base Locations				Value At Risk Total	Value At Risk Served	Total Weighted Dist.	Avg. Base-Fire Dist.	No. of Fires Total	No. of Fires Served	Value of Objective Function (Z)
135 - 143	2	7	4	3	23	22	1391.92	63.27	12	11	3008.08
144 - 149	8	4	5	0	15	15	534.71	35.65	7	7	2465.28
150 - 155	4	1	5	0	11	11	584.76	53.16	7	7	1615.24
156 - 165	8	4	5	3	46	45	3457.16	76.83	20	19	5542.84
166 - 169	8	1	3	6	97	83	5773.21	69.56	43	36	10826.73
170 - 171	6	8	9	5	56	55	3528.65	64.16	19	18	7471.34
172 - 173	9	8	6	3	90	90	5249.67	58.33	32	32	12750.33
174 - 174	2	10	8	3	41	40	3354.24	83.86	16	15	4645.76
175 - 175	5	0	0	0	1	1	94.26	94.26	1	1	105.74
176 - 176	7	6	0	0	9	9	713.26	79.25	3	3	1086.74
177 - 177	0	0	0	0	0	0	0.00	0.00	0	0	0.00
178 - 179	11	9	0	0	7	7	676.24	96.61	2	2	723.76
180 - 182	9	4	0	0	11	11	1060.78	96.43	4	4	1139.23
183 - 186	11	1	9	8	13	13	929.41	71.49	5	5	1670.60
187 - 196	8	1	9	0	19	19	1671.53	87.98	10	10	2128.46
197 - 197	10	7	9	6	16	16	1149.30	71.83	5	5	2050.70
198 - 207	2	10	11	3	33	26	1984.46	76.33	11	8	3215.54
208 - 208	0	0	0	0	0	0	0.00	0.00	0	0	0.00
209 - 211	2	10	9	6	41	41	2544.83	62.07	14	14	5653.16
212 - 216	10	8	7	6	52	51	3940.28	77.26	18	17	6259.72
217 - 218	10	7	3	6	22	20	1990.24	99.51	9	8	2009.78
219 - 227	8	10	4	6	24	21	1301.27	61.97	9	6	2898.73
228 - 230	8	0	0	0	3	3	230.99	77.00	1	1	369.01
	Total				630	599			248	229	

Table 2. Optimal Variable-Range Solution

Time Period	Airtanker Base Locations				Value At Risk		Total Weighted Dist.	Avg. Base-Fire Dist.	No. of Fires		Value of Objective Function (Z)
					Total	Served			Total	Served	
135 - 143	2	7	4	3	23	14	857.90	61.28	12	8	687.09
144 - 149	8	4	5	0	15	15	534.71	35.65	7	7	1385.28
150 - 155	1	4	0	0	11	9	434.12	48.24	7	5	420.89
156 - 165	8	4	5	3	46	16	842.18	52.64	20	9	602.82
166 - 169	8	5	3	6	97	40	1412.79	35.32	43	14	972.19
170 - 171	8	1	9	0	56	17	740.43	43.55	19	6	769.56
172 - 173	9	8	6	3	90	60	2367.71	39.46	32	20	2417.30
174 - 174	2	9	11	3	41	18	1127.11	62.62	16	7	1932.88
175 - 175	0	0	0	0	1	0	0.00	0.00	1	0	0.00
176 - 176	7	6	0	0	9	9	713.26	79.25	3	3	681.74
177 - 177	0	0	0	0	0	0	0.00	0.00	0	0	0.00
178 - 179	0	0	0	0	7	0	0.00	0.00	2	0	0.00
180 - 182	0	0	0	0	11	0	0.00	0.00	4	0	0.00
183 - 186	9	8	0	0	13	7	237.97	34.00	5	2	622.03
187 - 196	8	1	9	0	19	10	781.89	78.19	10	4	813.10
197 - 197	7	9	6	0	16	9	572.85	63.65	5	3	417.15
198 - 207	2	1	3	0	33	10	455.83	45.58	11	4	734.18
208 - 208	0	0	0	0	0	0	0.00	0.00	0	0	0.00
209 - 211	2	10	9	6	41	26	1256.10	48.31	14	9	703.89
212 - 216	8	6	0	0	52	15	795.90	53.06	18	5	179.09
217 - 218	10	6	0	0	22	6	437.33	72.89	9	2	762.68
219 - 227	8	1	4	6	24	11	428.01	38.91	9	4	961.99
228 - 230	0	0	0	0	3	0	0.00	0.00	1	0	0.00
	Total				630	292			248	112	

the variable-range model to determine revised values of the objective functions for all time periods. These results are presented in Table 3 in exactly the same manner as shown in Tables 1 and 2. The subsequent evaluation is presented in the form of an "overestimation index" attributed to the influence of these targets on the values of the objective function generated by the 200 km-limit solution.

Of itself overestimation of service potential is not all that critical. However, the consequences of determining unrealistic base locations are of concern and warrant analysis. In order to assess the outcome of incorrectly locating bases in response to fire occurrences, which in a more realistic sense could not be attacked according to the variable-range single strike limitations, an "index of locational superiority" was developed. This procedure resulted in elimination from consideration those fires originally within 200 km of a base but beyond the attack range determined by their prevailing hazard rating. For example, a fire originally included in the fixed-range solution might be located 180 km from a given base but, in reality, because of an FWI rating of 30 the fire should not be considered for treatment. If considered it would erroneously bias the base selection in favour of a given location. The actual development of these indices and their tabulation will be presented shortly.

In this undertaking the overall maximum acceptable strike range for bomber groups in Alberta has been

Table 3. Evaluation of Fixed-Range Bases According to Variable-Range Criterion

Time Period	Airtanker Base Locations				Value At Risk Total	Value At Risk Served	Total Weighted Dist.	Avg. Base-Fire Dist.	No. of Fires Total	No. of Fires Served	Value of Objective Function (Z)
135 - 143	2	7	4	3	23	14	857.90	61.28	12	8	687.09
144 - 149	8	4	5	0	15	15	534.71	35.65	7	7	1385.28
150 - 155	4	1	5	0	11	9	434.12	48.24	7	5	420.89
156 - 165	8	4	5	3	46	16	842.18	52.64	20	9	602.82
166 - 169	8	1	3	6	97	42	1590.95	37.88	43	15	924.03
170 - 171	6	8	9	5	56	16	691.41	43.21	19	5	753.58
172 - 173	9	8	6	3	90	60	2367.71	39.46	32	20	417.30
174 - 174	2	10	8	3	41	24	1635.46	68.14	16	9	1814.53
175 - 175	5	0	0	0	1	0	0.00	0.00	1	0	0.00
176 - 176	7	6	0	0	9	9	713.26	79.25	3	3	681.74
177 - 177	0	0	0	0	0	0	0.00	0.00	0	0	0.00
178 - 179	11	9	0	0	7	0	0.00	0.00	2	0	0.00
180 - 182	9	4	0	0	11	0	0.00	0.00	4	0	0.00
183 - 186	11	1	9	8	13	7	237.97	34.00	5	2	622.03
187 - 196	8	1	9	0	19	10	781.89	78.19	10	4	813.10
197 - 197	10	7	9	6	16	9	572.85	63.65	5	3	417.15
198 - 207	2	10	11	3	33	9	316.25	35.14	11	3	673.75
208 - 208	0	0	0	0	0	0	0.00	0.00	0	0	0.00
209 - 211	2	10	9	6	41	26	1256.10	48.31	14	9	703.89
212 - 216	10	8	7	6	52	15	795.90	53.06	18	5	179.09
217 - 218	10	7	3	6	22	6	437.33	72.89	9	2	762.68
219 - 227	8	10	4	6	24	10	321.46	32.15	9	3	868.54
228 - 230	8	0	0	0	3	0	0.00	0.00	1	0	0.00
	Total				630	297			248	112	

established as 200 km. This outer attack limit is approximately the same as that adopted by Hodgson and Newstead (1978 a, b) as being a reasonable limit of effectiveness for groups of two or three land based airtankers. The initial model run incorporates this attack distance and applies it to all fires considered for allocation regardless of the prevailing hazard (FWI) at the fire site. The second model run, considered in this study to yield the more realistic optimum solution, incorporates the variable maximum attack range governed by the fire hazard at the target. This is referred to as the "optimal variable-limit", "optimal variable" or "variable-range" solution, while the preceding run is referred to as the "optimal 200 km-limit", "200 km-limit", or "fixed-range" solution.

At this point it should be noted that there are occasions during the time periods under consideration when fewer than four base locations are designated as optimal. This occurs when less than the maximum number of four bases are required to serve all of the candidate fires within the prescribed attack range for each model run. During periods 177-177 and 208-208 fire occurrence was zero therefore no base locations were generated by either solution and it was assumed that the bomber groups retained their previous assignments for the purpose of the next iteration of the algorithm.

The two designated maximum attack range criteria were

considered initially and the objective functions for these model runs are presented in columns 2 and 5 of Table 4. In order to provide a basis for comparison of the performance of the 200 km-attack range, the base locations generated by it were submitted for evaluation in the variable-range model. This resulted in new values of the objective function, presented in column 3. The objective functions of the optimal 200 km solution were then divided by their counterparts produced by the integrated solution ($\frac{Z\ 200}{Z\ 200/Var.}$). This yielded an overestimation index of the extent to which the 200 km-limit results in overestimation of the value of the objective function, and correspondingly airtanker effectiveness potential, relative to the optimal variable solution. Finally, in order to assess the degree to which the optimal variable-range solution is truly superior to the fixed-range solution, it was necessary to introduce the sixth and last column in Table 4 ($\frac{Z\ Var.}{Z\ 200/Var.}$) which numerically indexes the relationship between the values of the objective functions generated by the variable range solution and those resulting from evaluation of the 200 km-limit bases in the variable-range model. This index of superiority indicates the extent to which the base locations identified in the variable-range model are better suited to maximization of the value-at-risk and number of fires served as traded-off with minimization of aggregate base-to-fire distance.

Analysis of model results indicates there to be two

Table 4. Comparison of Fixed-Range and Variable-Range Solutions

Time Period	Fixed-Range Solution Z 200	Fixed-Range Bases in Variable-Range Model Z 200/Var.	Overestimation Index Due to Unrealistic Base Locations Z 200 / Z 200/Var.	Optimal Variable-Range Solution Z Var.	Superiority Index Due to Improved Base Locations Z Var. / Z 200/Var.
135 - 143	3008.08	687.09	4.38	687.09	1.00
144 - 149	2465.28	1385.28	1.78	1385.28	1.00
150 - 155	1615.24	420.89	3.84	420.89	1.00
156 - 165	5542.84	602.82	9.19	602.82	1.00
166 - 169	10826.73	924.03	11.72	972.19	1.05
170 - 171	7471.34	753.58	9.91	769.56	1.02
172 - 173	12750.33	2417.30	5.27	2417.30	1.00
174 - 174	4645.76	1814.53	2.56	1932.88	1.07
175 - 175	105.74	0.00	∞	0.00	N/D
176 - 176	1086.74	681.74	1.59	681.74	1.00
177 - 177	0.00	0.00	0.00	0.00	N/D
178 - 179	723.76	0.00	∞	0.00	N/D
180 - 182	1139.23	0.00	∞	0.00	N/D
183 - 186	1670.60	622.03	2.69	622.03	1.00
187 - 196	2128.46	813.10	2.62	813.10	1.00
197 - 197	2050.70	417.15	4.92	417.15	1.00
198 - 207	3215.54	673.75	4 77	734.18	1.09
208 - 208	0.00	0.00	0.00	0.00	N/D
209 - 211	5653.16	703.89	8.03	703.89	1.00
212 - 216	6259.72	179.09	34.95	179.09	1.00
217 - 218	2009.78	762.68	2.63	762.68	1.00
219 - 227	2898.73	868.54	3.34	961.99	1.11
228 - 230	369.01	0.00		0.00	N/D
Totals and overall indices	77638.77	14727.49	5.27	15063.86	1.02

basic problems with the 200 km-limit solution. Initially, owing to the contributory influence of the consistently large (Sj - 200 km) maximum attack range in the algorithm, the objective functions produced by the 200 km-limit solution are several times larger than similar values in the optimal variable solution. By evaluating the results of the fixed-range solution in the variable-range model, a more realistic measure of the performance of the so-called optimal base locations was determined than was recorded for the initial model run where Sj = 200. The resultant overestimation indices range from 0 to infinity. Where there was no change in the value of the objective function, the index was zero. Where the objective function declined to zero from some larger value in the 200 km-limit model run, then the index takes on an infinitely large value. Overall, the performance of the fixed-range model overestimates airtanker success potential, owing to unrealistic base locations, by a factor of 5.27. This is determined by dividing the total value of the objective functions in column 2 of Table 4 by the total value in column 3.

The second problem associated with the use of a single unrestricted attack range, in this case 200 km, concerns the disadvantages of suboptimal base locations. Airtanker group locations determined to be optimal by this solution could well involve greater average strike distances and serve fewer fires and lower values-at-risk than a truly optimal model based on more realistic strike distances. Since the

latter is considered to yield superior results, the objective functions of the variable-range solution and those resulting from evaluation of fixed-range bases according to the variable-range criterion have been compared and indexed according to the level of superiority of the optimal variable model. The resultant indices presented in Table 4 indicate that in 5 of the 17 non-zero time periods, the optimal solution showed some level of superiority although the extent appears to be limited since there was no demonstrated improvement in excess of 11% (1.11). Where evident, superiority stemmed from the improvement in the optimal base locations, and respective objective functions produced by the variable-range solution. During time periods 170 - 171, 198 - 207, and 219 - 227, the greater numbers of fires and larger values-at-risk served contributed to the larger values of the objective function, and subsequently to the superiority of the optimal model solution, at the expense of slightly larger average base-to-fire distances. The converse contributed to the larger objective functions for the remaining two periods (166 - 169 and 174 - 174) where superiority was evident in the variable-range solution. This is the manner in which the algorithm employed in this thesis trades off the level of coverage provided with the minimization of service distance, within a specified maximum limit, to yield the highest possible objective function.

As an example of what happens when the more realistic

base locations and objective function values are produced, consider the fifth time period, between days 166 and 169. Here the overestimation index is recorded at 11.72 owing to the determination of unrealistic base locations. On the other hand, when the airtanker groups are properly located according to the optimal variable model, the solution is better by 5% (1.05). The initial model run allocated 36 out of a total of 43 fires within the 200 km attack range, to the four optimal bases (Figure 4). However, when these same bases and the more realistic variable attack ranges were considered there were only 15 fires within range of the same four bases (Figure 5). This is one more fire served than in the optimal variable solution where, despite the lower number of fires and value-at-risk served, the objective function was larger than in the previous solution and therefore considered superior. Figure 6 displays the results of the optimal variable-limit solution for the time period under consideration.

In another example situation during the period between days 219 and 227. The overestimation index is relatively low (3.34). This stems from the location of a group at Calgary (10) according to the 200 km-limit solution instead of Footner Lake (1) as determined by the optimal variable solution. Consequently, the optimal solution offers an 11% (1.11) improvement in the value of the objective function owing to the better location of this one base, since the others (8, 4, and 6) remain the same. Although there is a

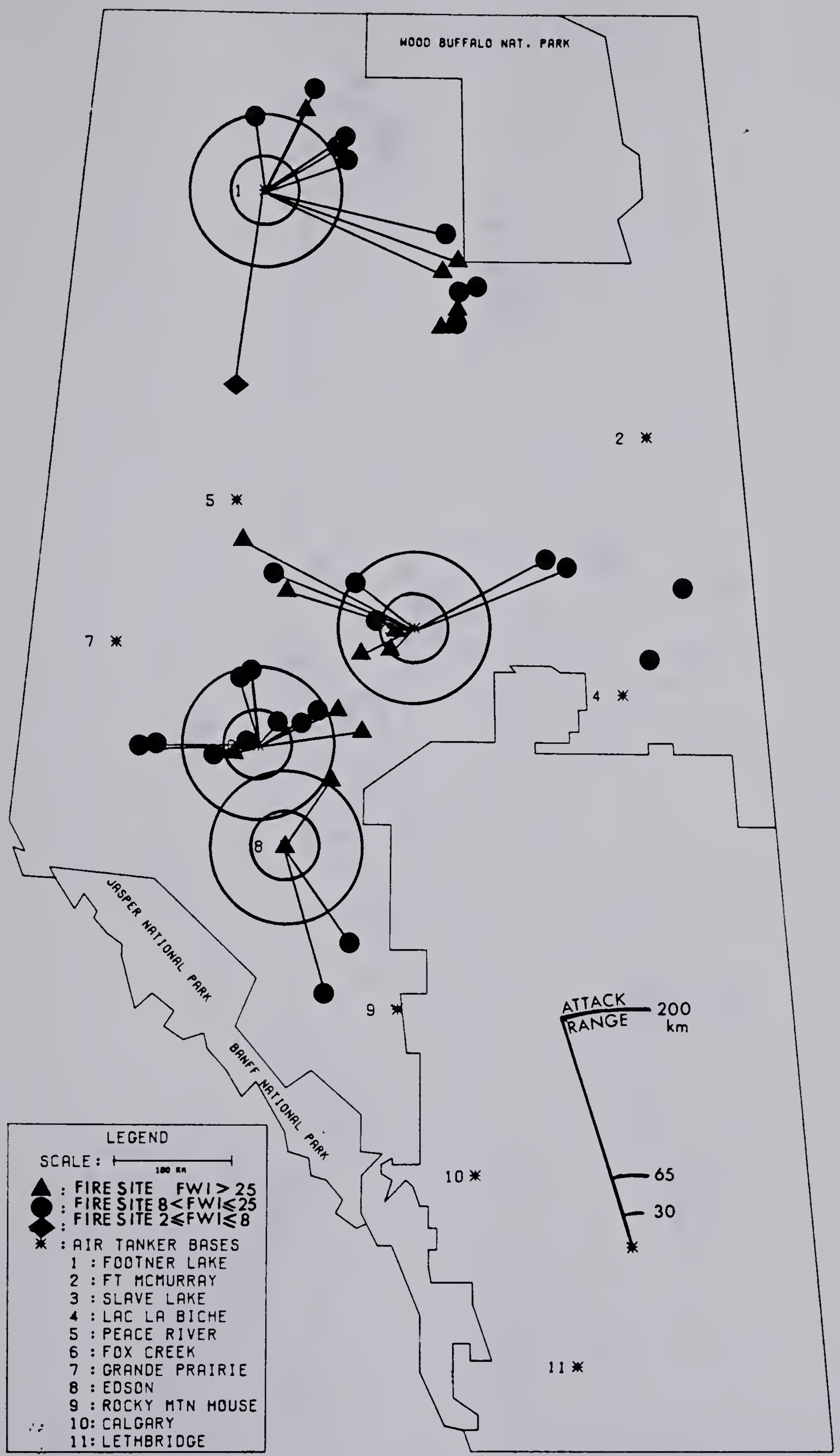

Fig. 4. Days 166-169, Fixed-Range Criterion, Optimal Solution.

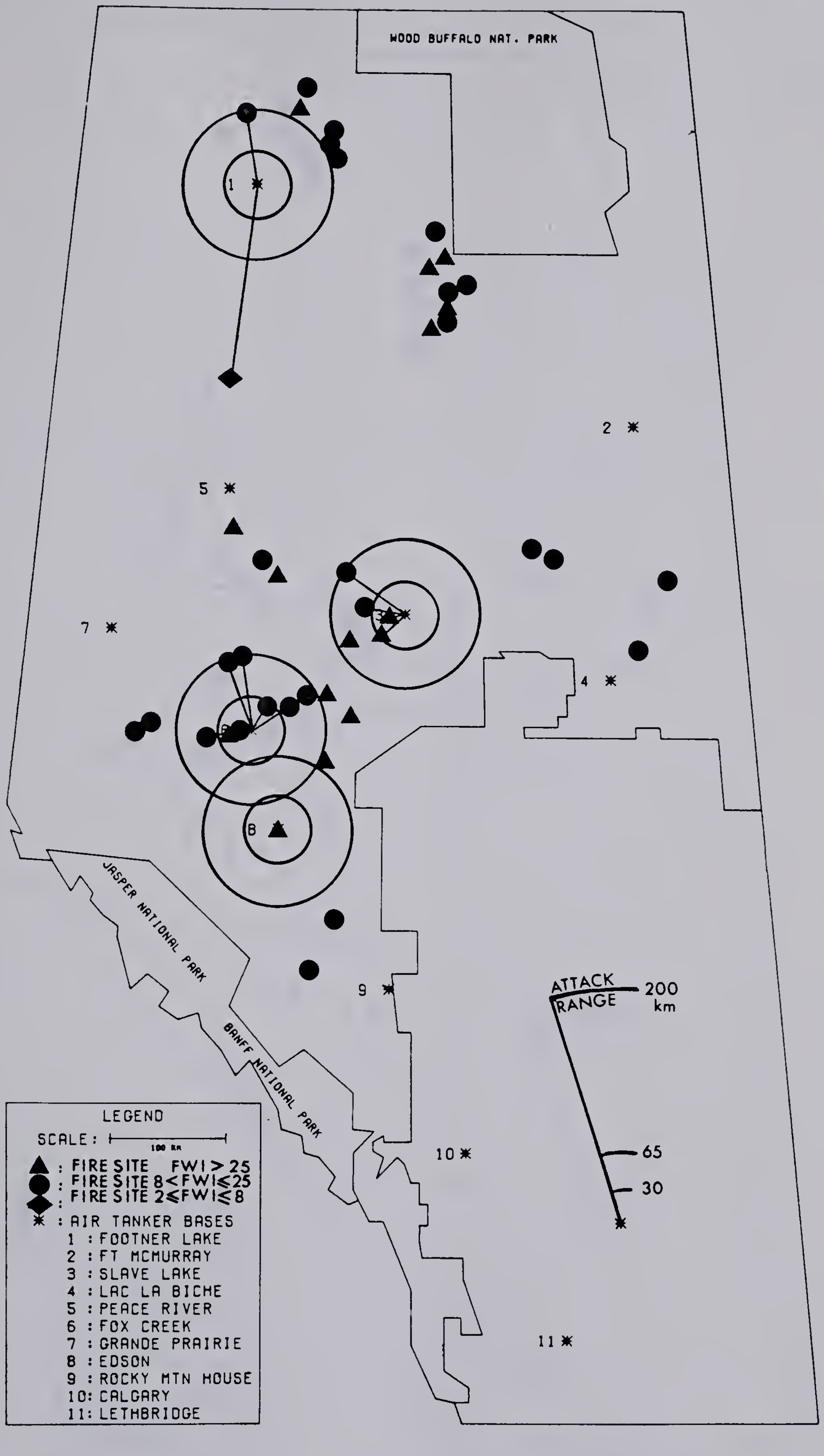

Fig. 5. Days 166-169, Variable-Range Criterion, Evaluation of Fixed-Range Bases.

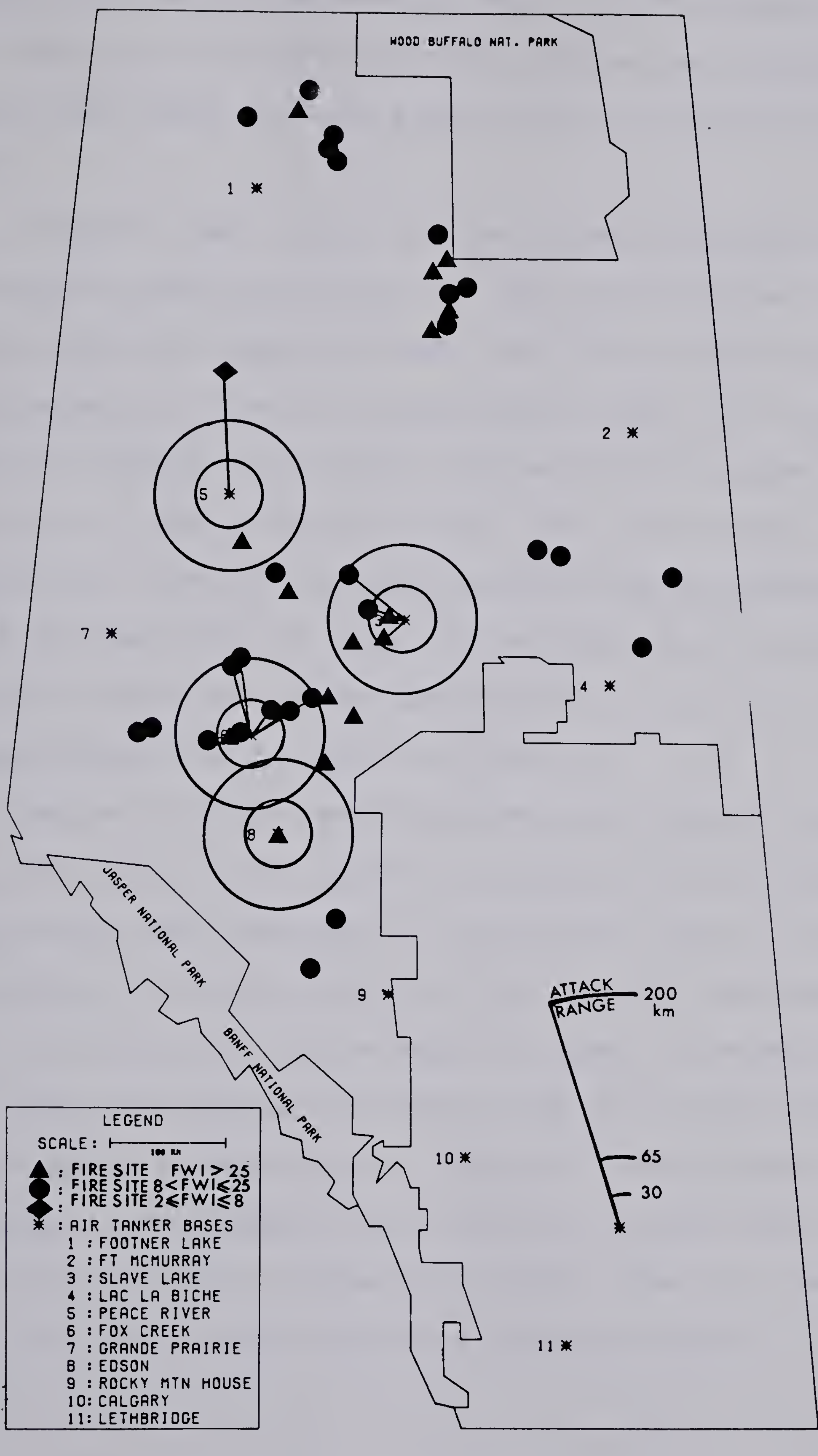

Fig. 6. Days 166-169, Variable-Range Criterion, Optimal Solution.

slight increase in the average base-to-fire distance, the additional unit of value-at-risk and the one additional fire served contribute to this superiority as reflected in the index.

In most cases (12 of 17) the optimal variable solution offered no superiority over the 200 km-limit bases evaluated in the variable-range solution, and the key base locations designated by either performed equally well. In 5 cases the level of superiority was not defined (N/D) because of null solutions in the integrated model run. For example, in period 212 - 216, the optimal solution determined bases 8 and 6 at Edson and Fox Creek to be adequate to maximize the objective function. On the other hand, of the four bases designated by the 200 km-limit solution (10, 8, 7, and 6), only the two at Edson and Fox Creek were needed to generate the same value of the objective function and therefore equal superiority when compared to the optimal results. The bases at Calgary (10) and Grande Prairie (7) were redundant in their contributions to the model outcome. An example of a case where the optimal variable range did prove superior is exhibited in a comparison of Figures 5 and 6 where the locational advantages of positioning a bomber group in Peace River are superior to those of Footner Lake by a factor of 1.05, the other three locations being the same.

B. Consequences of Immobility in Locating Airtanker Groups

This phase of model output analysis deals with a comparison of results provided by the optimal variable-range model and those produced when the optimal base locations are maintained for each subsequent fire occurrence period. This treatment enables assessment of the consequences of a lack of mobility in maintaining an airtanker basing schedule readily adapted to the requirements of changing fire occurrence demands. Accordingly, this analysis considers each set of optimal base locations in terms of how well a new fire occurrence pattern could be served during the ensuing time period - a retrospective interpretation of the merits of maintaining a flexible and responsive aerial attack program.

Again, this analysis is best demonstrated by preparing a comparative output table to interpret the relationship between the values of the objective functions produced by the L-A algorithm in each model run. This particular phase of the analysis will show that the results of the optimal variable solution are generally better than or at least as good as those produced when the base locations remain unchanged for the subsequent time period.

A summary of information contained in the model run as determined by the L-A algorithm is presented in Table 5. It should be noted that there are only 22 time periods represented in this table because all have been advanced one time frame. Accordingly, the optimal base locations

Table 5. Evaluation of Bases from Previous Period in Variable-Range Model

Time Period	Airtanker Base Locations				Value At Risk Total	Value At Risk Served	Total Weighted Dist.	Avg. Base-Fire Dist.	No. of Fires Total	No. of Fires Served	Value of Objective Function (Z)
144 - 149	2	7	4	3	15	11	482.24	43.84	7	5	772.75
150 - 155	8	4	5	0	11	7	162.22	23.17	7	3	292.79
156 - 165	1	4	0	0	46	2	80.56	40.28	20	2	184.44
166 - 169	8	4	5	3	97	18	527.19	29.29	43	7	427.81
170 - 171	8	5	3	6	56	10	486.03	48.60	19	3	568.97
172 - 173	8	1	9	0	90	48	2064.03	43.00	32	16	1535.97
174 - 174	9	8	6	3	41	17	1013.59	59.62	16	6	1306.40
175 - 175	2	9	11	3	1	0	0.00	0.00	1	0	0.00
176 - 176	0	0	0	0	9	0	0.00	0.00	3	0	0.00
177 - 177	7	6	0	0	0	0	0.00	0.00	0	0	0.00
178 - 179	0	0	0	0	7	0	0.00	0.00	2	0	0.00
180 - 182	0	0	0	0	11	0	0.00	0.00	4	0	0.00
183 - 186	0	0	0	0	13	0	0.00	0.00	5	0	0.00
187 - 196	9	8	0	0	19	9	598.64	66.52	10	3	796.35
197 - 197	8	1	9	0	16	6	720.32	120.05	5	2	74.68
198 - 207	7	9	6	0	33	3	476.74	158.91	11	1	123.26
208 - 208	2	1	3	0	0	0	0.00	0.00	0	0	0.00
209 - 211	0	0	0	0	41	2	134.07	67.04	14	1	265.93
212 - 216	2	10	9	6	52	12	601.21	50.10	18	4	178.78
217 - 218	8	6	0	0	22	3	185.48	61.83	9	1	414.52
219 - 227	10	6	0	0	24	3	62.06	20.69	9	1	132.94
228 - 230	8	1	4	6	3	0	0.00	0.00	1	0	0.00
	Total				630	151			248	55	

initially determined by the variable-range solution for the first period between days 135 and 143 are held constant for the second period. This means that the airtanker groups originally located at Fort McMurray (2), Grande Prairie (7), Lac La Biche (4) and Slave Lake (3) during the first time period in Table 2 remain in these locations during period two between days 144 and 149 and so on throughout the balance of the season. Table 6 is a comparison of the values of the objective functions tabulated in Tables 2 and 5 and presents, in the form of a superiority index, the relationship between the two model runs - the optimal variable-range solution and the previous period evaluated in the variable-range model.

The optimal variable solution offers locational advantages which are equal to or superior to those resulting from holding the airtanker groups in place for the subsequent periods. The comparative indices in Table 6 range from equality (1.00) to infinitely superior (∞) in terms of the objective functions determined. These results suggest that in order to maximize the opportunity for airtanker groups to respond to variable fire occurrence patterns throughout the province, there must be flexibility in the positioning schedule so that the available groups are optimally located. It can been shown that locational immobility results in a reduction in the potential effectiveness of bomber groups as demonstrated in the following example situation.

Table 6. Comparison of Results, Previous Period Base Locations Evaluated in Variable-Range Model

Time Period	Optimal Variable-Range Solution	Previous Period Bases in Variable-Range Model	Superiority Index Due To Optimal Solution
	Z Var	Z Prev/Var	Z Var / Z Prev/Var
135 - 143	687.09		
144 - 149	1385.28	772.75	1.79
150 - 155	420.89	292.79	1.44
156 - 165	602.82	184.44	3.27
166 - 169	972.19	427.81	2.27
170 - 171	769.56	568.97	1.35
172 - 173	2417.30	1535.97	1.57
174 - 174	1932.88	1306.40	1.48
175 - 175	0.00	0.00	N/D
176 - 176	681.74	0.00	∞
177 - 177	0.00	0.00	N/D
178 - 179	0.00	0.00	N/D
180 - 182	0.00	0.00	N/D
183 - 186	622.03	0.00	∞
187 - 196	813.10	796.35	1.02
197 - 197	417.15	74.68	5.59
198 - 207	734.18	123.26	5.96
208 - 208	0.00	0.00	N/D
209 - 211	703.89	265.93	2.65
212 - 216	179.09	178.78	1.00
217 - 218	762.68	414.52	1.84
219 - 227	961.99	132.94	7.24
228 - 230	0.00	0.00	N/D
Total	15063.86	7075.59	Overall Index 2.13

During the time period between days 156 and 165 when the bomber groups, originally positioned at Footner Lake (1), Lac La Biche (4), and two other bases of no consequence (0), as shown in Figure 7, are held in place, their capability to respond to the ensuing fire occurrence pattern is greatly reduced. By comparison, the objective function is maximized in the optimal solution when these airtanker groups are stationed at Edson (8), Lac La Biche (4), Peace River (5) and Slave Lake (3), as shown in Figure 8. The optimal solution serves 14 more fires and an additional 7 units of value-at-risk resulting in a superiority index of 3.27 (Table 6).

At this point, it could be questioned whether or not the two previous null locations (0) might have been among those designated as optimal during the subsequent period. If so, the present level of superiority would not have been as evident. In another situation one might question which two of four bases would be best relocated to optimize the solution if only two bases were required during the subsequent period. Clarification of this limitation in the present inter-base transfer routine follows.

As this L-A model now stands, the algorithm incorporates a random initial starting solution as it seeks to optimize the base locations which best satisfy the objective function. By iteration the optimal bases are eventually determined for each time period. However, as noted earlier, if fewer than four bases are required to

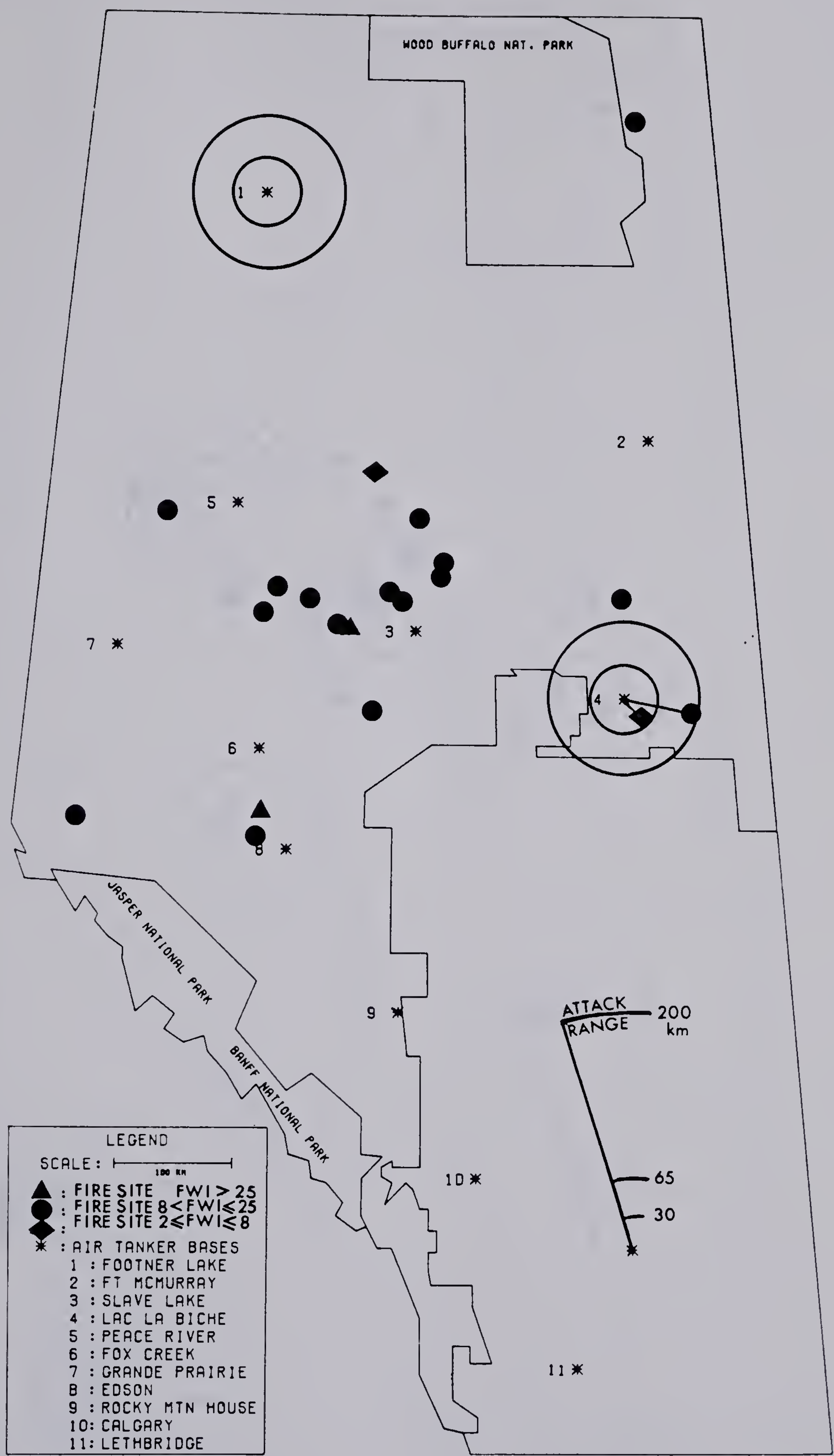

Fig. 7. Days 156-165, Variable-Range Criterion, Evaluation of Previous Period Bases.

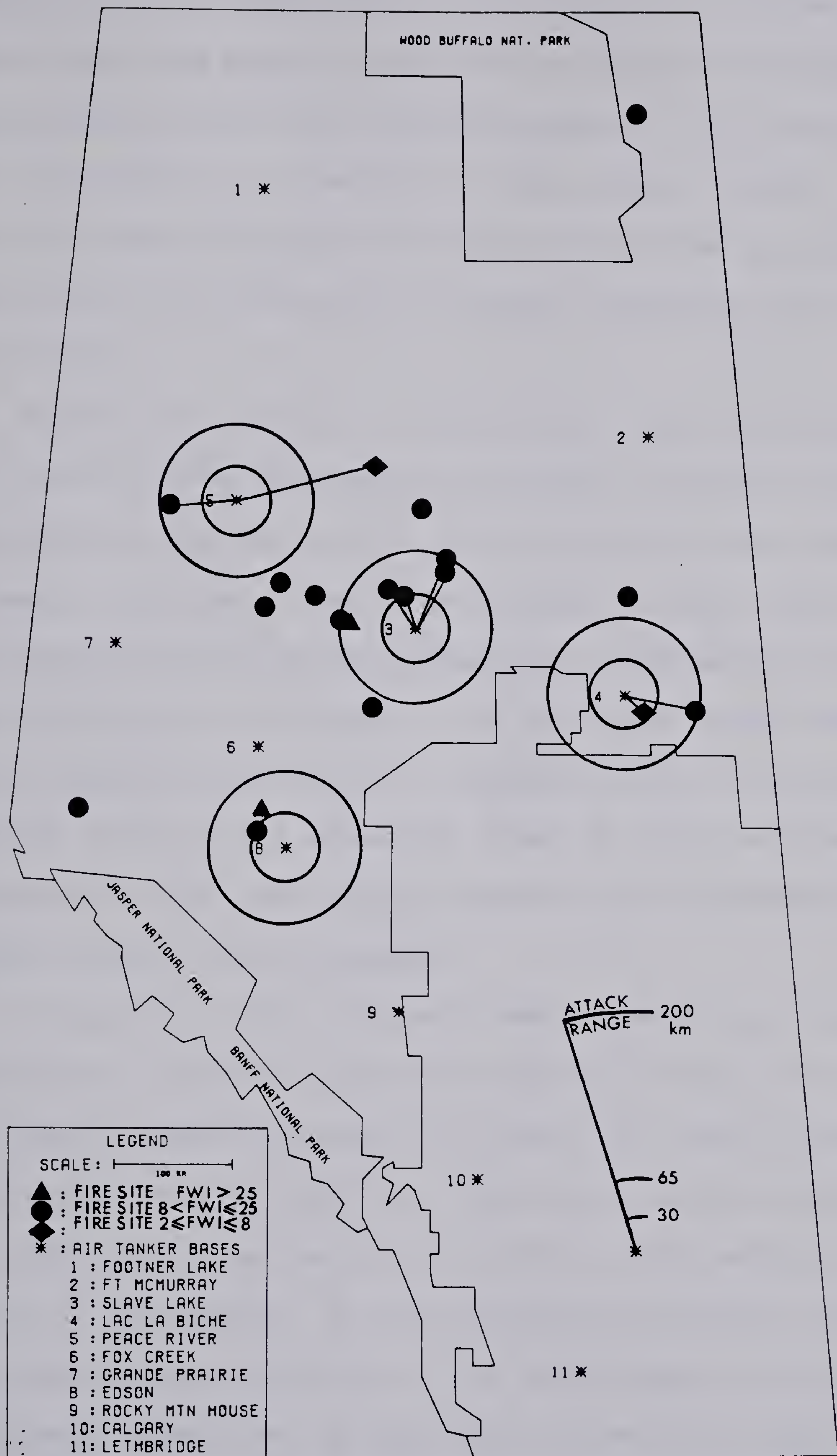

Fig. 8. Days 156-165, Variable-Range Criterion, Optimal Solution.

serve all of the candidate fires then it is assumed that those remaining groups retain their previous assignment for the purpose of the next iteration period. As a result these null locations, as presented in the summary tables, could well bias the outcome of this portion of the analysis dealing with an evaluation of group transfers and locational flexibility.

Within the context of the present model structure and until such a time as specific transfer rules are available nothing more can be done to determine which base locations, if fewer than four, should be changed to best serve the fire occurrence pattern of any subsequent time period. Future consideration of the question of airtanker group mobility should address this matter in greater detail if more specific results are expected. Some of these options will be presented in the concluding chapter when recommendations for future research are discussed.

In spite of this inherent model limitation, overall, the optimal variable solution presently offers an indexed locational superiority of 2.13 times that which results from holding the previous period's base locations constant for one additional time period. In other words, within the limits of this model, as fire occurrence patterns change from one period to the next, the advantages of transferring airtankers among the various bases offer more than two times the ability to respond to prevailing fire starts.

The foregoing analysis has been directed toward the

testing and evaluation of the performance of a location - allocation model designed to reflect the influence of fire hazard on the maximum attack distances of bomber groups and subsequently the optimality of their base locations. The consequences of using a single or constant maximum attack range, initially introduced by Hodgson and Newstead (1978 a, b), have been analyzed. These results were compared with those generated by using three distinct FWI dependent attack ranges in order to demonstrate the level of locational improvement offered by the latter. Additional analysis dealt with the implications of locational inflexibility in the positioning of airtanker groups to respond to changing fire occurrences patterns from one time period to the next.

It was found that there is a strong tendency for the initial model run, governed by a fixed attack range, to overestimate the likelihood of success of the four bomber groups on the basis of comparative values of the objective function. When these locational results were considered in a more realistic sense by evaluating them in the variable-range model, the extent of overestimation was determined and presented in the form of an index. Similarly, when these model results were compared with those of the optimal variable solution, it became apparent that the latter solution offered locational superiority in some cases and equivalent in others. In summary, the fixed attack range results in substantial overestimation of mission success potential, however, in most circumstances this is of little

consequence because the locational superiority offered by the variable solution is often unaffected when those fires beyond the defined ranges of attack of the variable-limit model are dropped.

In terms of the values of the objective functions as determined by the L-A algorithm in the optimal variable-range model, it has been shown that it is important that airtanker group mobility be achieved consistent with changing fire occurrence conditions. Although demonstrated on the basis of historical fire occurrence and scheduling statistics, it becomes apparent that initial attack programs must incorporate sufficient flexibility to readily transfer aerial attack capabilities among designated bases to provide the required level of response as will no doubt be governed by varying demand criteria and the nature of the resource values threatened. The one major impediment in a program such as this is the present lack of ability to anticipate and/or predict the localities wherein fire occurrence probabilities are highest and demands on initial attack resources are greatest. For example, it may be more advantageous to be prepared to deal with fire starts in a high value, high hazard region than to be taking action on fires in a low priority and/or low hazard region.
Given that the predictive capabilities of fire control organizations can be enhanced with improved interpretation of fire risk and ignition potential, coupled with better weather and fuels information, location-allocation modelling

could see operational implementation in aid of more informed decision-making.

The following chapter will be devoted to a more in-depth investigation of the relationships between the output of the two optimal solutions and the actual period-by-period base locations exhibited in the AFS airtanker deployment roster for 1974.

V. COMPARISON OF ACTUAL BASE LOCATIONS AND THOSE PRODUCED BY THE TWO OPTIMIZATION MODELS

This chapter analyses the differences between the actual 1974 AFS airtanker fleet deployment schedule and the two levels of model output depicting optimal base locations during twenty-three distinct time periods.

The two models tested seek to trade off maximization of value-at-risk coverage with minimization of aggregate base-to-fire distance according to previously described priority ratings and attack range criteria. In each case maximization of the objective function by the L-A algorithm yields an optimal solution for the time period under consideration. The purpose of this analysis is to evaluate the consequences of these model solutions with respect to the known basing schedule and the results it provides for the same time periods during the 1974 fire season.

In the preceding chapter, the two model runs, referred to as the variable-range solution and the fixed-range solution, were analyzed in order to assess the relative merits of each. It was shown that the fixed-range criterion consistently overestimated airtanker performance potential according to predefined effectiveness criteria. This was demonstrated by evaluating the base locations determined by this model in the optimal variable-distance model. This enabled examination of these locations under more realistic circumstances by giving consideration to declining airtanker

effectiveness with increasing base-to-fire distance and fire hazard. A superiority index resulting from this treatment indicated that the variable-range model provided the better base locations in that the values of the objective functions were equally as good as or superior to those achieved with the 200 km-attack range.

The concluding phase of model output analysis will be presented in this chapter in two segments. Initially, the actual base locations recorded for each of the 1974 time periods under study will be compared with those generated by the optimal variable-distance model. Secondly and similarly, the actual bases will be compared with the locations determined according to the 200 km-range criterion.

A. Actual Bases Evaluated According to the Variable-Range Criterion

In order to assess the relationship between the actual basing schedule and that which was determined to be optimal according to the variable attack range model, it was necessary to compare the values of the objective functions determined by the L-A algorithm using as input variables the actual base locations for each time period under review. In this way the model is used to determine the value-at-risk and number of fires served as well as the minimum aggregate base-to-fire distance and the objective function for each centroid or base locaton derived from the 1974 positioning roster. These results are presented in Table 7 in the same

Table 7. Actual Bases Evaluated According to Variable-Range Criterion

Time Period	Airtanker Base Locations				Value At Risk Total	Value At Risk Served	Total Weighted Dist.	Avg. Base-Fire Dist.	No. of Fires Total	No. of Fires Served	Value of Objective Function (Z)
135 - 143	7	2	1	3	23	10	397.58	39.76	12	4	482 42
144 - 149	3	2	1	0	15	4	752.37	188.09	7	1	47.63
150 - 155	3	2	1	4	11	9	434.12	48.24	7	5	420.89
156 - 165	7	2	1	3	46	10	649.31	64.93	20	5	270.69
166 - 169	7	3	1	6	97	38	1590.95	41.87	43	14	804.03
170 - 171	7	3	6	0	56	3	252.89	84.30	19	1	347.11
172 - 173	7	3	8	0	90	18	1482.44	82.36	32	6	1307.55
174 - 174	9	3	8	0	41	17	1013.59	59.62	16	6	1306.40
175 - 175	9	2	3	8	1	0	0.00	0.00	1	0	0.00
176 - 176	9	2	4	8	9	6	894.14	149.02	3	2	305.86
177 - 177	9	2	9	7	0	0	0.00	0.00	0	0	0.00
178 - 179	10	2	3	7	7	0	0.00	0.00	2	0	0.00
180 - 182	10	2	1	7	11	0	0.00	0.00	4	0	0.00
183 - 186	10	2	3	7	13	3	453.68	151.22	5	1	146.33
187 - 196	10	2	1	7	19	4	774.40	193.60	10	2	25.60
197 - 197	10	9	1	7	16	6	457.12	76.19	5	2	337.88
198 - 207	10	9	8	7	33	3	536.28	178.76	11	1	63.72
208 - 208	7	10	8	9	0	0	0.00	0.00	0	0	0.00
209 - 211	7	10	9	0	41	15	794.67	52.98	14	5	180.32
212 - 216	7	10	8	9	52	3	194.69	64.90	18	1	0.31
217 - 218	7	10	8	3	22	6	607.40	101.23	9	2	592.60
219 - 227	7	10	8	7	24	3	168.15	56.05	9	1	26.85
228 - 230	7	10	8	3	3	0	0.00	0.00	1	0	0.00
	Total				630	158			248	59	

manner as the results of the model runs were presented in the preceding chapter. Again, it should be noted that there are a number of initial attack periods during which base locations are identified by one or more zero entries in the output summary tables. In the case of the optimal solutions these null locations mean that the designated fires were within striking distance of fewer than the maximum four potential bases, while in the actual basing schedule more than one group may have been assigned to a given base thereby reducing the total number of air attack centres occupied by airtankers.

In addition, the relative performance of the actual and optimal bases in satisfying the requirements of the objective function have been tabulated from Tables 2 and 7 and presented in the form of a "superiority index" for each time period, in Table 8. This tabulation serves as a basis for comparison of the two solutions in such a way that the overall and period specific advantages of the optimal basing schedule can be demonstrated.

On the basis of this rating procedure, the optimal variable-distance model offers locational advantages ranging from 1.00 to 577.71 times those of the actual schedule. In those circumstances where there were no fires within striking distance of the designated bases (i.e. null solutions) the two model runs produced undefined results indicated by N/D. During the 17 periods when the optimal solutions indicated superiority there were 5 instances when

Table 8. Comparison of Results, Actual Base Locations Evaluated in Variable-Range Model

Time Period	Optimal Variable-Range Solution	Actual Bases in Variable-Range Model	Superiority Index Due To Optimal Solution
	Z Var	Z Act/Var	Z Var / Z Act/Var
135 - 143	687.09	482.42	1.42
144 - 149	1385.28	47.63	29.08
150 - 155	420.89	420.89	1.00
156 - 165	602.82	270.69	2.23
166 - 169	972.19	804.03	1.21
170 - 171	769.56	347.11	2.22
172 - 173	2417.30	1307.55	1.85
174 - 174	1932.88	1306.40	1.48
175 - 175	0.00	0.00	N/D
176 - 176	681.74	305.86	2.23
177 - 177	0.00	0.00	N/D
178 - 179	0.00	0.00	N/D
180 - 182	0.00	0.00	N/D
183 - 186	622.03	146.33	4.25
187 - 196	813.10	25.60	31.76
197 - 197	417.15	337.88	1.23
198 - 207	734.18	63.72	11.52
208 - 208	0.00	0.00	N/D
209 - 211	703.89	180.32	3.90
212 - 216	179.09	0.31	577.71
217 - 218	762.68	592.60	1.29
219 - 227	961.99	26.85	35.83
228 - 230	0.00	0.00	N/D
Total	15063.86	6666.19	Overall Index 2.26

the level of superiority exceeded a factor of 10.

The various features of this level of analysis can be best demonstrated by way of example situations wherein locational superiority is evident. For instance, during the second time period, between days 144 and 149, the bases actually occupied by airtanker groups were Slave Lake (3) (two groups), Fort McMurray (2) and Footner Lake (1). Here, only one fire, of a total of 7 was allocated to the Slave Lake base (Figure 9). On the other hand, at optimality, tanker groups based at Edson (8), Lac La Biche (4) and Peace River (5) could have taken action all 7 fires in the province (Figure 10). By comparison, the optimal solution offers 29 times the superiority or effectiveness potential in terms of value-at-risk and number of fires served as reflected in the respective values of the objective function. Also this is accomplished with a much lower average base-to-fire distance of 36 km as opposed to 188 km for the actual solution.

In another example, during the 15th time period between days 187 and 196, the actual locations were Calgary (10), Fort McMurray (2), Footner Lake (1), and Grande Prairie (7). Two of the 10 fires, having a total value-at-risk of 4 units, are allocated to the bases at Grande Prairie and Footner Lake (Figure 11). The optimal solution places groups at Edson (8), Footner Lake (1) and Rocky Mountain House (9). As a result, 4 of the 10 fires and 10 of the 19 value-at-risk units are within range of these bases as governed by

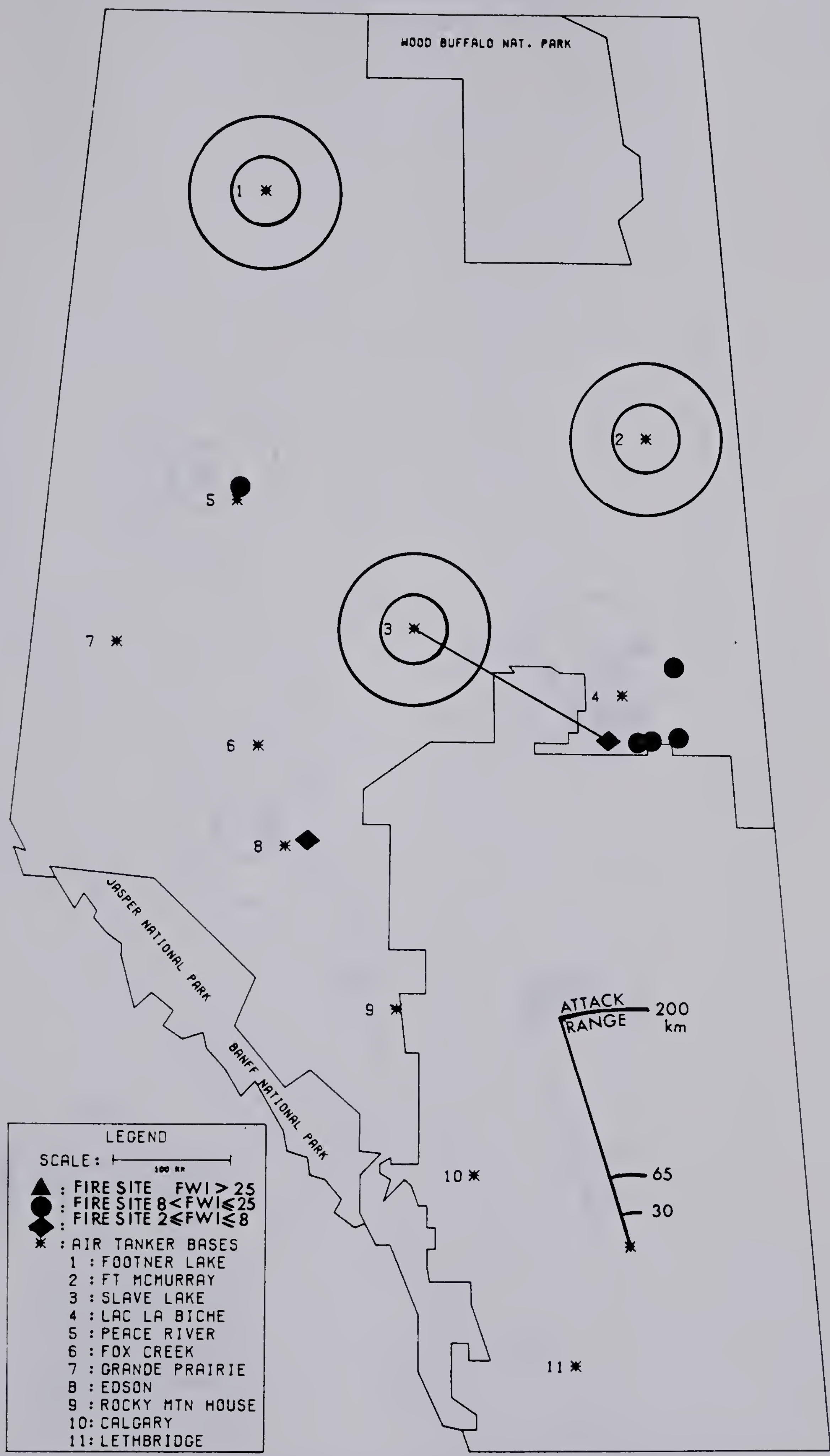

Fig. 9. Days 144-149, Variable-Range Criterion, Evaluation of Actual Base Locations.

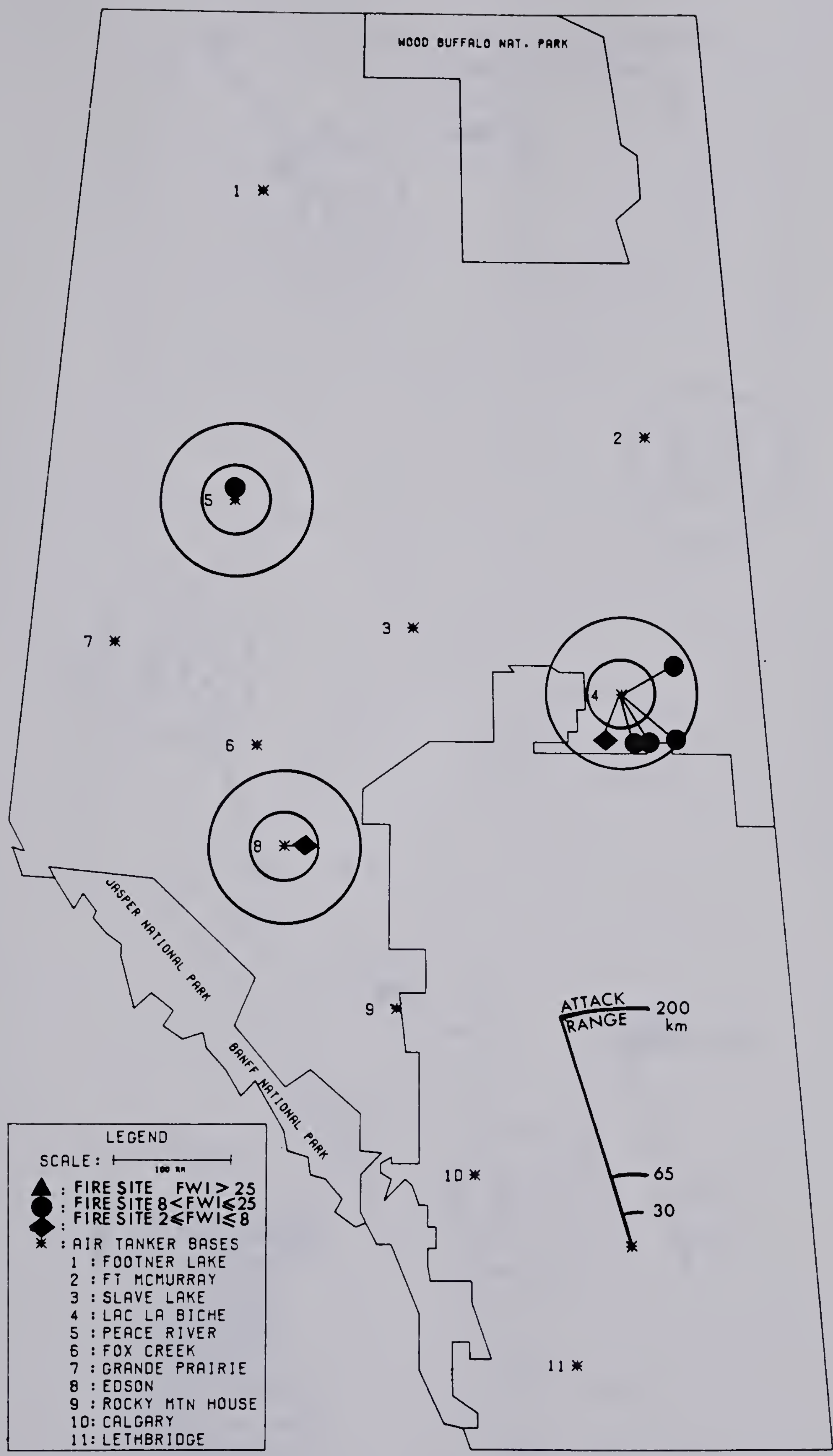

Fig. 10. Days 144-149, Variable-Range Criterion, Optimal Solution.

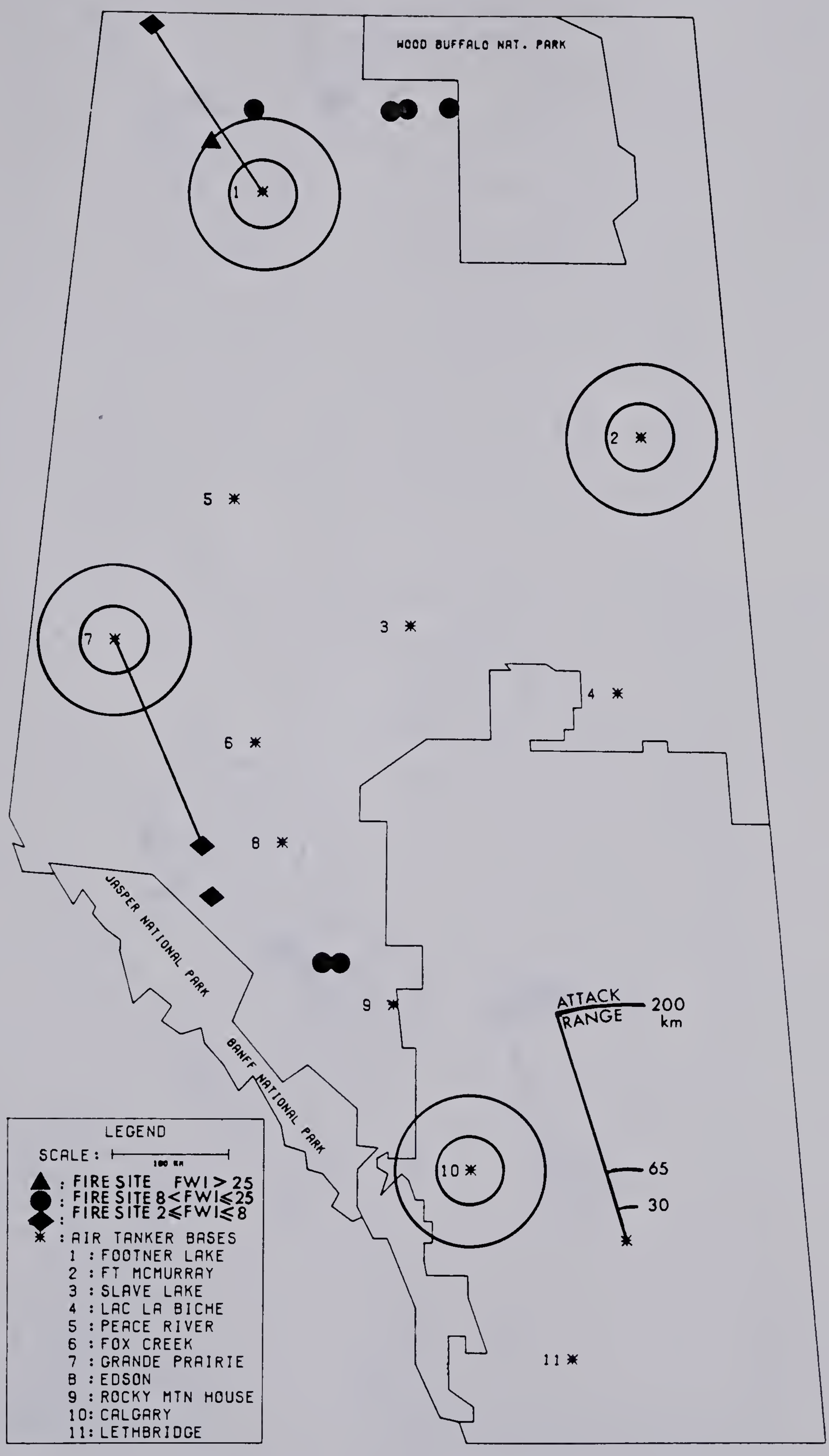

Fig. 11. Days 187-196, Variable-Range Criterion, Evaluation of Actual Base Locations.

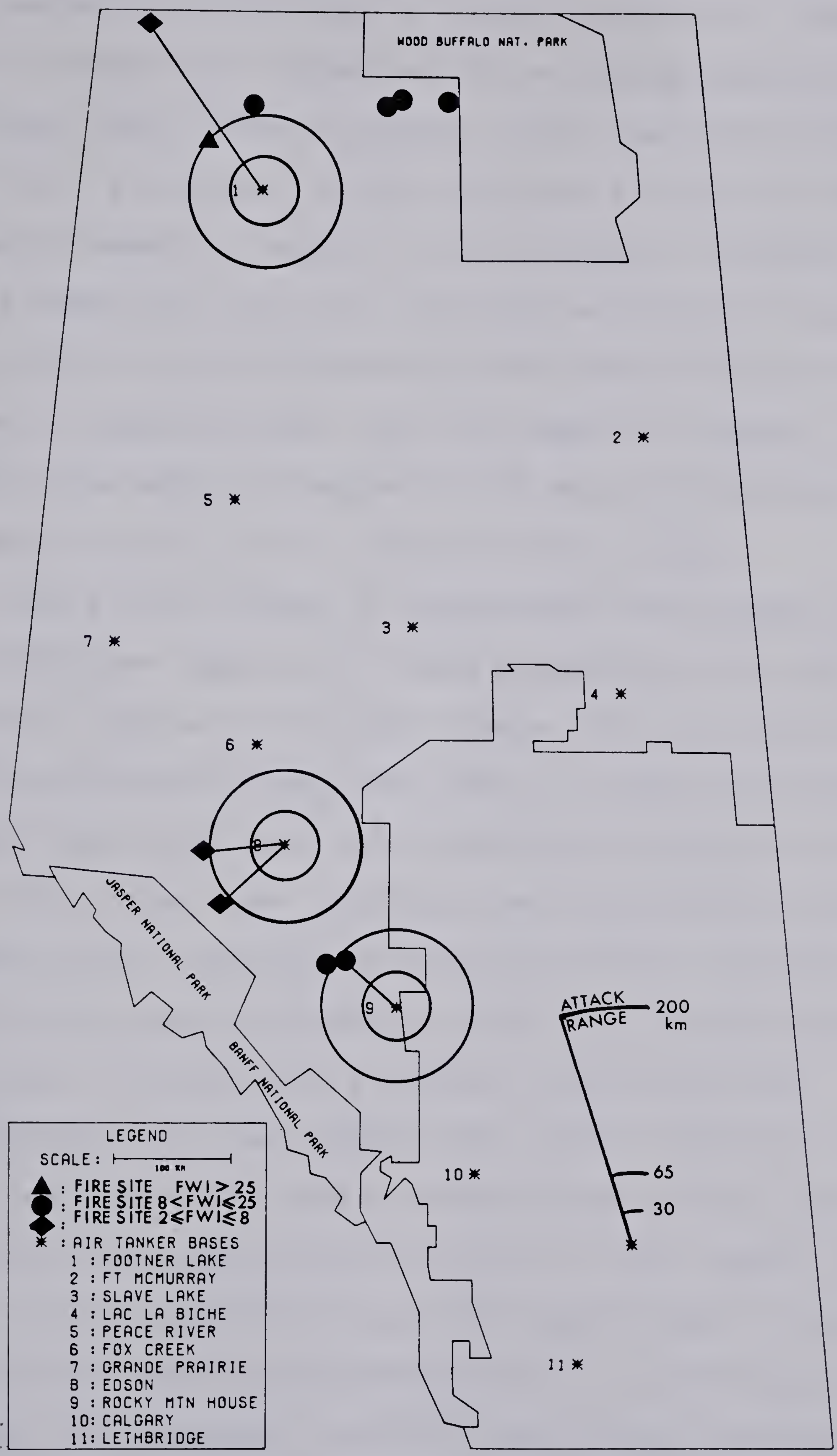

Fig. 12. Days 187-196, Variable-Range Criterion, Optimal Solution.

the variable attack range criterion (Figure 12). There is also a concomitant reduction in the average base-to-fire distance from 194 km to 78 km. In this case the optimal solution is superior to the actual by a factor of almost 32 times as shown in Table 8. In this example situation, there are a number of fires (5) north and northeast of Footner Lake which are not allocated to that base in either of the actual or optimal model runs. As shown in Figures 11 and 12 these fires were all beyond the 30 km or 65 km attack range as determined by their respective FWI ratings.

There are a number of reasons why the optimal base locations are superior to those presented in the 1974 basing schedule. Basically the model deals with historical fire occurrence data thereby enabling it to determine those optimal base locations which maximize the objective function while the actual base locations were determined originally without prior knowledge of fire occurrence locations particularly when regional or provincial trends were not apparent. In actuality, airtankers would often be transferred to a new location only after sufficient demand for their services could be demonstrated during a particular phase of fire suppression activity. In this regard, the model is not constrained by either operational or economic limitations normally considered prior to deciding on base changes. Furthermore, in 1974, a definitive resource valuation or protection priority was not in effect. Accordingly, airtanker base changes could not be justified

on the basis of value-at-risk, a prime component of the L-A algorithm employed in this model. Finally, initial strike distance limits have not been imposed to date by the AFS This too is a factor which in the present model contributes to the determination of optimal base locations as service distance minimization is traded off with maximization of value-at-risk, while under actual circumstances airtankers might have flown great distances to take action on one or more fires before returning to their original bases.

B. Actual Bases Evaluated According to the Fixed-Range Criterion

In the previous chapter it was shown that the results determined using the 200 km-range were less satisfactory than those recorded in the optimal variable-limit solution. This was because the former range continually resulted in overestimation of the capabilities of four airtanker groups when compared with the latter solution which incorporated hazard dependent attack distances. Furthermore, this resulted in the determination of less realistic base locations which in turn provided inferior service potential as governed by the intent of the objective function.

In this segment of the analysis, the locational output of the 200 km-limit solution will be compared with the actual basing schedule for 1974 for the same 23 time periods considered earlier. Once again a comparative performance index will be used to describe the relationship between the

two in terms of how well each satisfies the requirements of the objective function when the maximum attack range is fixed at 200 km. The values of the objective functions compiled in Tables 1 and 9 are presented in Table 10 to form the basis for comparison.

The comparison index is referred to as a "superiority index due to the optimal solution" because as in the previous comparison (Table 8), the optimal solution yields equal or larger values of the objective function during each time frame. With the exception of the three periods for which there are null solutions, the optimal solution provides larger values of the objective function owing to the greater value-at-risk and number of fires served. In one case the optimal solution is infinitely larger where the optimal base locations could serve one fire whereas in the actual solution, none of the designated bases were within the maximum 200 km attack range. During the remaining 19 periods the optimal solution resulted in superior base locations ranging from 1.03 to 42.8 times better than those actually occupied in 1974.

Two time periods have been selected to demonstrate the indexed relationship between the optimal and actual basing schedules. These are the second period between days 144 and 149 and the 12th period between days 178 and 179.

In the first instance, the model solution is superior to the actual by a factor of almost 43 times. Here the optimal solution (Table 1) places airtanker groups at Edson

Table 9. Actual Bases Evaluated According to Fixed-Range Criterion

Time Period	Airtanker Base Locations				Value At Risk		Total Weighted Dist.	Avg. Base-Fire Dist.	No. of Fires		Value of Objective Function (Z)
					Total	Served			Total	Served	
135 - 143	7	2	1	3	23	19	1004.31	52.86	12	8	2837.89
144 - 149	3	2	1	0	15	7	1342.40	191.77	7	3	57.59
150 - 155	3	2	1	4	11	11	626.00	56.91	7	7	1574.00
156 - 165	7	2	1	3	46	40	3957.60	98.94	20	16	4042.81
166 - 169	7	3	1	6	97	80	6012.48	75.16	43	35	9987.46
170 - 171	7	3	6	0	56	42	3435.52	81.80	19	14	4964.47
172 - 173	7	3	8	0	90	87	9736.65	111.92	32	31	7663.31
174 - 174	9	3	8	0	41	33	2810.01	85.15	16	12	3789.98
175 - 175	9	2	3	8	1	0	0.00	0.00	1	0	0.00
176 - 176	9	2	4	8	9	6	894.14	149.02	3	2	305.86
177 - 177	9	2	9	7	0	0	0.00	0.00	0	0	0.00
178 - 179	10	2	3	7	7	4	692.31	173.08	2	1	107.69
180 - 182	10	2	1	7	11	5	745.77	149.15	4	2	254.24
183 - 186	10	2	3	7	13	11	1907.56	173.41	5	3	292.45
187 - 196	10	2	1	7	19	10	1449.96	145.00	10	7	550.04
197 - 197	10	9	1	7	16	16	1428.01	89.25	5	5	1772.00
198 - 207	10	9	8	7	33	24	3169.37	132.06	11	7	1630.64
208 - 208	7	10	8	9	0	0	0.00	0.00	0	0	0.00
209 - 211	7	10	9	0	41	39	3751.03	96.18	14	13	4048.98
212 - 216	7	10	8	9	52	51	5220.55	102.36	18	17	4979.47
217 - 218	7	10	8	3	22	20	2160.31	108.02	9	8	1839.70
219 - 227	7	10	8	7	24	17	1421.15	83.60	9	5	1978.85
228 - 230	7	10	8	3	3	3	230.99	77.00	1	1	369.01
	Total				630	525			248	197	

Table 10. Comparison of Results, Actual Base Locations Evaluated in Fixed-Range Model

Time Period	Optimal Fixed-Range Solution Z 200	Actual Bases in Fixed-Range Model Z Act/200		Superiority Index Due To Optimal Solution Z 200 / Z Act/200
135 - 143	3008.08	2837.89		1.06
144 - 149	2465.28	57.59		42.81
150 - 155	1615.24	1574.00		1.03
156 - 165	5542.84	4042.81		1.37
166 - 169	10826.73	9987.46		1.08
170 - 171	7471.34	4964.47		1.50
172 - 173	12750.33	7663.31		1.66
174 - 174	4645.76	3789.98		1.23
175 - 175	105.74	0.00		∞
176 - 176	1086.74	305.86		3.55
177 - 177	0.00	0.00		N/D
178 - 179	723.76	107.69		6.72
180 - 182	1139.23	254.24		4.48
183 - 186	1670.60	292.45		5.71
187 - 196	2128.46	550.04		3.87
197 - 197	2050.70	1772.00		1.16
198 - 207	3215.54	1630.64		1.97
208 - 208	0.00	0.00		N/D
209 - 211	5653.16	4048.98		1.40
212 - 216	6259.72	4979.47		1.26
217 - 218	2009.78	1839.70		1.09
219 - 227	2898.73	1978.85		1.46
228 - 230	369.01	369.01		1.00
Total	77638.77	53046.44	Overall Index	1.46

(8), Lac La Biche (4) and Peace River (5) where 7 out of 7 fires and 15 out of 15 value-at-risk units are served (Figure 13). The actual schedule (Table 9), on the other hand, sites groups at Slave Lake (3) (2 groups), Fort McMurray (2) and Footner Lake (1). During this period, 3 fires and 7 value-at-risk units within the 200 km attack range could potentially have been allocated to these bases (Figure 14).

In another example situation, during the 12th time period between days 178 and 179, the optimal solution yields a locational advantage of almost 7 times that of the actual (Table 10). Here the model selects bases at Lethbridge (11) and Rocky Mountain House (9) in order to maximize the value of the objective function; and, in so doing, serves the total value-at-risk (7 units) and all of the fires in the province (2) (Figure 15). By comparison the actual schedule placed bomber groups at Calgary (10), Fort McMurray (2), Slave Lake (3), and Grande Prairie (7). At these locations only 4 value-at-risk units and one fire could have been served from the base at Calgary (Figure 16).

Comparison of the overall superiority indices in Tables 8 and 10 for all of the 23 time periods indicates that the optimal variable solution offers greater overall locational superiority over the actual base locations (2.26) than the optimal 200 km-limit solution (1.46). This observation is in direct support of the intent of this thesis to evaluate airtanker effectiveness potential relative to maximum strike

Fig. 13. Days 144-149, Fixed-Range Criterion, Optimal Solution.

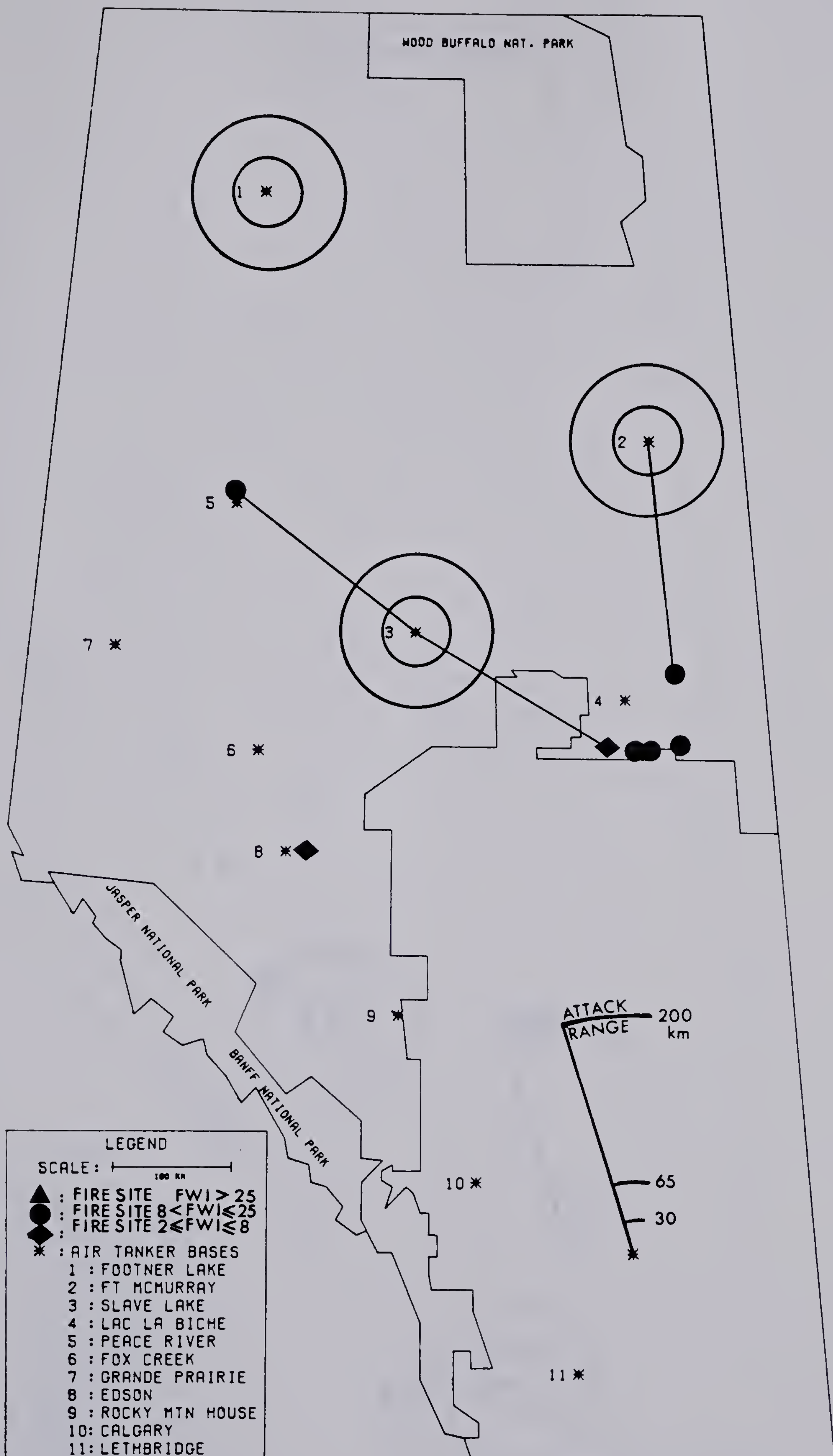

Fig. 14. Days 144-149, Fixed-Range Criterion, Evaluation of Actual Base Locations

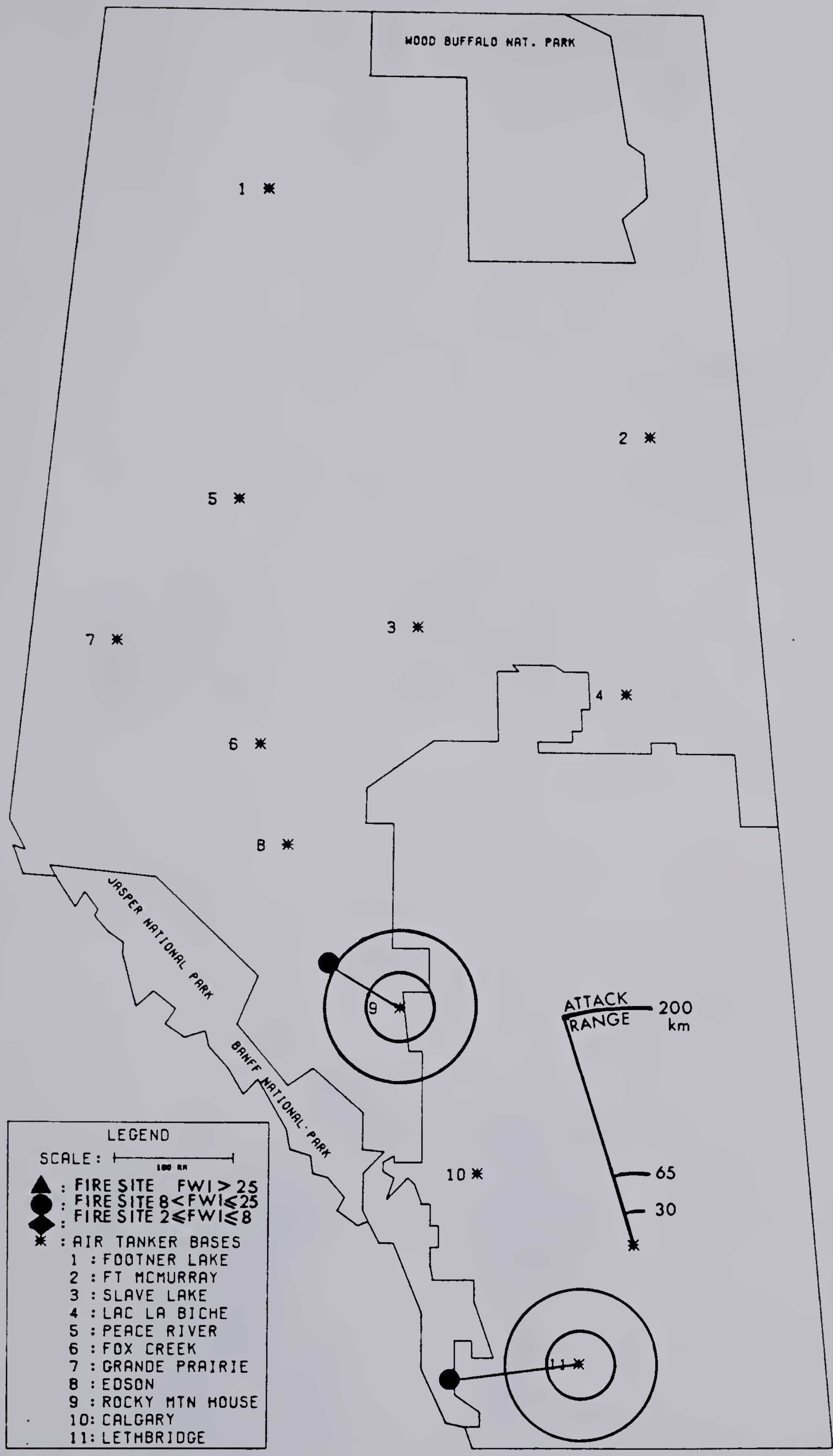

Fig. 15. Days 178-179, Fixed-Range Criterion, Optimal Solution.

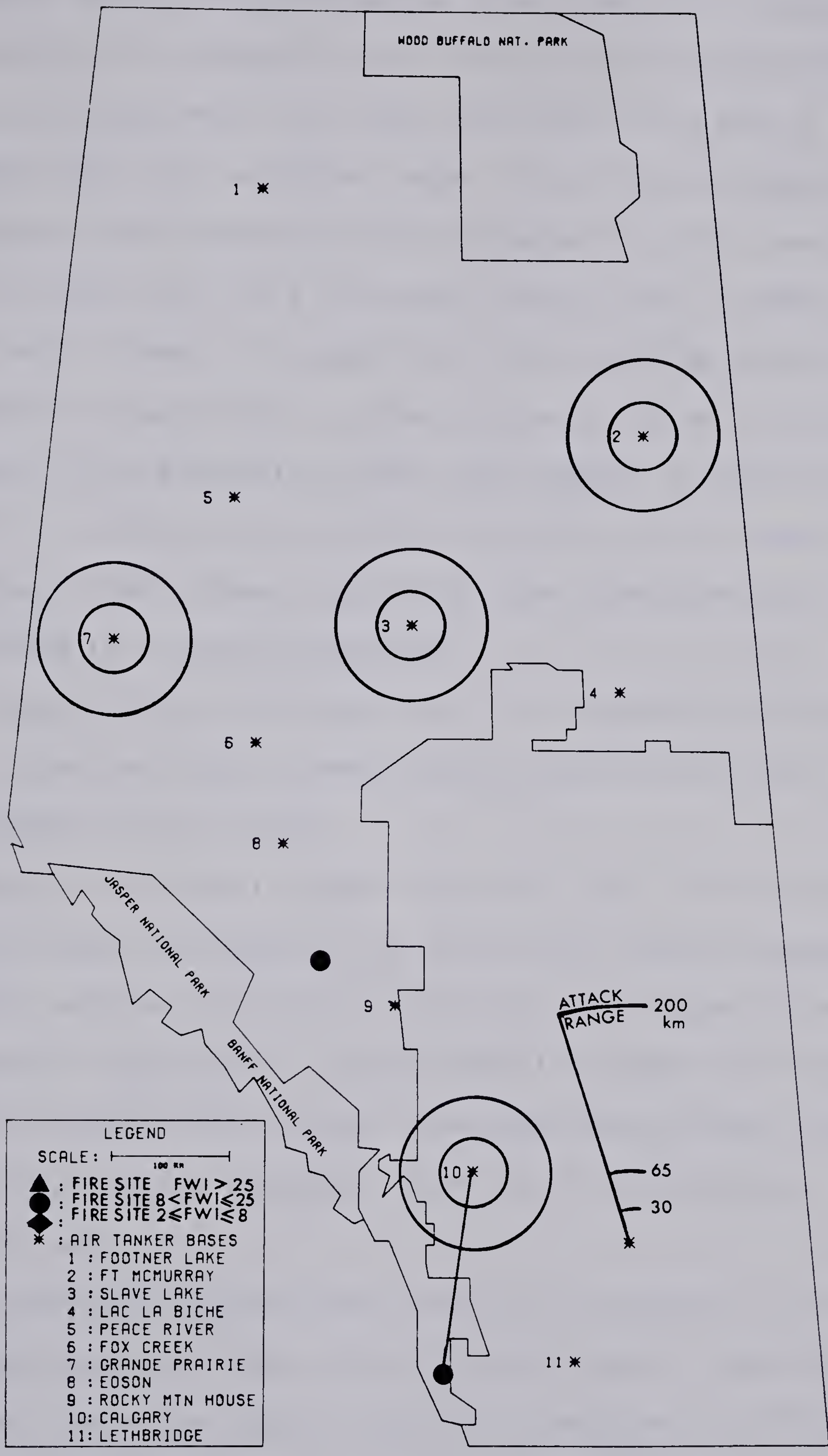

Fig. 16. Days 178-179, Fixed-Range Criterion, Evaluation of Actual Base Locations.

distances which are governed by prevailing fire hazard. By association this suggests that the actual basing schedule during 1974 was more like that resulting from use of the 200 km-range than the variable range. This in turn suggests that the operational maximum strike distance for that year was probably more akin to a constant 200 km than to some shorter or variable range. In support of the preceding observation, reference is again made to the constant 193 km attack range referred to by McDonald (1976) and Hodgson and Newstead (1978 a, b) which does not give consideration to decremental airtanker effectiveness potential over distance with increasing fire hazard ratings.

In concluding this analysis, it is appropriate to present the pertinent comments which can be derived from this aspect of the study.

1. Analysis of model output indicates that the optimal solutions are superior to the actual basing schedule of 1974 and the resultant locational advantages offer a greater opportunity to maximize the number of fires and the value-at-risk served from designated bases while minimizing the aggregate base-to-fire distances involved.
2. Although not a great deal better, the optimal variable model solution does offer greater overall superiority over the actual base locations than does the 200 km-limit solution.
3. The actual base locations occupied in 1974 offered

better performance relative to the results of the 200 km-limit solution than the optimal variable solution, which suggests that a singular long-range attack distance was likely in force at that time rather than some fire hazard regulated range or ranges.

In summary, there are a number of "operational" circumstances which in addition to the obvious benefits affiliated with the use of empirical data serve to explain discrepancies between the modelled and actual base locations. The optimal variable solution, which incorporates fire hazard related initial strike distance criteria, offers superior locational results when compared with those produced by the fixed-range model. The latter, on the other hand, seems to have more closely approximated the outcome of the 1974 schedule when the actual bases were evaluated in the model.

The final chapter of this thesis along with summary comments and conclusions will be devoted to a discussion of some of the limitations of this modelling experience and some of the implications of modelling "real-world" events of the 1974 fire season. Additional research requirements needed to improve upon this initial attempt to optimize the location of airtanker resources in Alberta will be introduced.

VI. SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

The foregoing chapters of this thesis have been used to introduce the problem of positioning a limited number of airtanker groups in response to varying fire occurence situations in Alberta. Following the introduction and development of a suitable location-allocation algorithm, two airtanker base location optimization model solutions were analyzed and discussed in comparison with one another and with the actual airtanker positioning schedule for the 1974 fire season. This concluding chapter will be devoted to summary and concluding comments as well as an assessment of the strengths and weaknesses of this undertaking along with recommended actions for additional study and improvement.

A. Summary

It is generally understood that there are three functional levels of fire management activity maintained in anticipation of wildfire outbreaks. Fire prevention is directed at reducing fire occurrence through public education, law enforcement, and reduction of fire hazard and risks. Presuppression activities include those organizational, training, and management functions performed in advance of fire occurrence. Fire suppression concerns those fire control activities directed toward the actual extinguishment of wildfires following their detection.

Aside from fire prevention programs which are aimed at excluding the occurrence of unwanted fire, presuppression activities are probably the most significant in terms of a protection agency's preparedness to meet fire control objectives. In Alberta this function is to a large degree under centralized control particularly where province-wide fire management planning, administration, and policy making are concerned. The airtanker program is an excellent example of an AFS presuppression activity which falls within the jurisdiction of forest protection headquarters and for this reason offers investigative opportunities in the area of location-allocation modelling.

This program is a key component of Alberta's initial attack objectives which are directed at minimizing the costs and losses incurred as a result of wildfire occurrence. The high costs, mobility, speed, and fire containment potential offered by airtankers coupled with their limited numbers are such that optimization of their usefulness on a province-wide scale is a matter of continuing concern to the AFS. This thesis has endeavored to consider one element of this concern by investigating the problem of optimizing the locations of four airtanker groups among a greater number of potential bases such that coverage of threatened resource values can be maximized in a trade-off with minimization of the aggregate base-to-fire initial strike distance.

Following a review of the pertinent literature it was concluded that because of the importance of distance in

airtanker initial strike effectiveness, models of this sort should incorporate a distance- effectiveness function even if at the expense of some measure of coverage - in this case value-at-risk. The present study has carried airtanker location research an additional step forward in recognizing that initial attack effectiveness is not only influenced by strike distance but also by the fire hazard at the target site. Accordingly, the Hodgson and Newstead (1978b) algorithm was modified to make allowances for this concern and the maximum strike range was adjusted to account for three fire hazard categories ranging from moderate to extreme values of the Canadian Fire Weather Index.

B. Conclusions

Two location-allocation model runs were applied to 1974 fire occurrence data compiled for 23 distinct time periods for which the actual airtanker group locations were known. The first was referred to as the "fixed-range" or "200 km-limit" solution and was run as a basis for comparing resultant optimal base locations with those produced by the second, referred to as the "optimal variable-range" solution. The latter gave consideration to the negative influence of increasing fire hazard on the maximum attack range of airtanker groups.

Comparison of the results of these two model runs indicated that the fixed-range model overestimated the effectiveness potential of the airtanker groups owing to the

determination of unrealistic base locations. When these locations were evaluated in the variable-range model the optimal base locations proved to be inferior to those generated by the latter, in most instances.

Additional analysis considered the implications of locational inflexibility in positioning airtanker groups to respond to changing fire occurrence patterns from one time period to the next. This investigation into the consequences of airtanker immobility was conducted by holding group locations constant within the optimal variable-range model during each subsequent time period under study; and it was shown that the optimal solution was superior in all instances. Clearly, aerial initial attack programs must be sufficiently flexible to enable airtanker groups to be transferred among those bases which maximize their opportunity to provide the desired level of service.

In the second phase of analysis the actual base locations provided by the 1974 basing schedule were compared with the two optimal solutions. Here it was shown that in each case the locations generated by the model were superior to the actual locations in terms of satisfying the objective function. Furthermore, the optimal variable solution offered slightly greater overall superiority over the actual base locations than the fixed-range solution. Finally, it was concluded that the actual locations were somewhat more akin to those produced by the 200 km-attack range, suggesting that the 1974 initial strike range was probably not governed

by fire hazard conditions at the target.

It has been observed that the use of historical fire occurrence data in this study, coupled with various operational constraints, have given the model a decided advantage in determining optimal base locations. For this reason, it is appropriate that a few additional concluding comments give recognition to some of the limitations encountered in modelling "real world" events and circumstances.

One limiting feature of this model stems from the use of a simple objective function to optimize the location of a limited number of resource units among a finite number of locations in discrete space. Since this is a rather limited spatial optimization technique it is dependent only upon some measure of distance. In this application, distance is weighted by a predetermined "value-at-risk" surrogate. Only a much more dynamic model involving computer simulation techniques could adequately account for the diversity of economic, temporal, productivity, and fire behaviour parameters. Simard (1978) has considered the complexity of these variable aerial attack conditions in his airtanker productivity simulation model, AIRPRO. His model is the result of an exhaustive investigation into the interaction of a multitude of airtanker and fire related parameters and is designed to perform an economic appraisal of air attack alternatives. No doubt, some of Simard's (1979) AIRPRO model results will prove beneficial in advancing more operational

versions of the model introduced in this thesis, as future developments take place.

Inasmuch as this model has considered some of the implications of airtanker resource mobility in responding to ever changing fire occurrence situations, no attempt was made to explain specific activities that actually occurred. A general, but limited, discussion of some of the activities of these groups follows:

There is a major difference between the operational aspects of an aerial attack program and the results of this study as becomes evident following a review of the 1974 basing schedule. During this fire season there were several long periods of time when groups were assigned to particular bases regardless of the provincial fire situation. This can be directly attributed to the logistical or service and support constraints imposed on a bomber group which requires parts and other scheduled and emergency maintenance services, affiliated retardant mixing crews, accommodation and other sustenance services. In other words, relocation of an aerial attack group involves a lot more than simply transferring aircraft and pilots. These many associated facilities must travel overland to accompany their respective groups at each new location. For example, what might seem like a two-hour base change, from Fort McMurray to Footner Lake, could actually involve almost three days in transferring and re-establishing aircraft and crews.

Thus, it becomes obvious that the operational

inflexibility of an aerial attack organization cannot be accounted for by a simple spatial optimization model. This argument is strengthened during the period between May 24 and June 18 (144-169) when the model did not once designate Fort McMurray as an optimal base location. According to the actual assignment roster one B-26 group was positioned at this base throughout the entire period, when it could have been more effectively located among several other bases in the province. In fact only one fire was actually attacked in the Athabasca Forest from the base at Fort McMurray throughout the balance of the season. This same situation can be identified at other times during the course of the 1974 fire season. For example, there were no fires actually attacked from the Lac La Biche base while, according to the model, this base could have played a significant role during the initial month of the airtanker contract. Again, it becomes strongly evident that models based upon recorded information have a real advantage over decisions based upon limited information at the original time and place.

Further to the foregoing discrepancies between the model and the "real world" events, there are also examples of bomber groups taking initial action from bases beyond the models' maximum permissible 200 km attack range. There are also circumstances wherein bombers have been diverted from their original target dispatch to take action on alternate target(s) possibly because of a multiple fire occurrence situation requiring priority re-evaluation or because of

some inability to locate the original target. There are also occasions when missions have been aborted because of unneccessary dispatches, usually as a result of false alarms. Also, during the 1974 season, group locations were biased in favour of the Fox Creek, Edson, and Slave Lake bases in mid-June because of the outbreak of the 9400 ha Judy Creek fire in the Swan Hills, where they provided support action. Some groups were also amalgamated at that time in support of the Judy Creek fire activity thus somewhat affecting their subsequent initial attack range and locational advantages.

C. Recommendations for Future Research

Models of the sort developed in this study are not likely to see application in the course of everyday operational activity. However, since they are dependent upon the availability of operational data, it seems reasonable to assume that their outcome could influence operations policies and management guidelines at least in a general way at some future date. In other words, a certain amount of hindsight is required when considering future action. Other more extensive or interactive models such as those involving computer simulation exercises may prove to be more versatile and applicable to operational routines to the extent that they become day-to-day management tools.

The results of this particular undertaking have suggested that an added degree of mobility is required in

the positioning of airtanker groups to optimize their locations with respect to changing fire occurrence patterns. It has been pointed out that operational constraints would be encountered but it is clear that there are definite advantages associated with being in the right place at the right time. Future L-A modelling dealing with airtanker groups should consider the development and incorporation of group transfer or base shifting rules. These might be governed by distance criteria which reflect the temporal or economic factors involved in ordering a base change under present operational circumstances. Possibly such rules could dictate that only the next closest uncommitted group(s) should be considered for re-location. Fire hazard or priority ratings might serve as guidelines in support of this decision process. There may be multiple occurrence outbreaks following regionalized lightning activity when transfer rules might call for amalgamation of attack groups if the suppression capacity of normal group arrangements is likely to be inadequate.

The foregoing suggestions concerning the need for improved flexibility and mobility within an airtanker program could be significantly enhanced and modelled much more readily if better fire prediction capabilities were developed. This would enable optimal base locations to be identified before the fact instead of after. To avoid some of the pitfalls likely to be associated with very specific predicted fire and weather parameters, a more stochastic

approach might be taken. Rather than rely on questionable predictions there are no doubt opportunities to develop stochastic data in a manner similar to that reported by Cunningham and Martell (1973). They showed that the number of man-caused fires that occur each day in an Ontario protection district can be represented by a Poisson distribution. Bookbinder and Martell (1979) further assume that the probability distribution of lightning caused fires that occur each day is also Poisson.

Additional research is contemplated to investigate the influence of multiple fire occurrence situations on airtanker allocation and dispatch procedures and their subsequent capabilities under stress conditions. Along this line Bookbinder and Martell (1979) have described a time-dependent queueing approach to modelling the allocation of helitack crews to initial attack helicopter bases when the number of fire starts may exceed the availability of helitack resources. Also, P.M. Kourtz of the Petawawa National Forestry Institute has been developing algorithms during the past several years to assist in aerial patrol route planning.

There are other means, as well, to improve the functionalism of the present model or future generations of it. For example, it would be beneficial to introduce more sensitive fire weather parameters such as initial spread index (ISI) and build-up index (BUI) rather than rely solely on the less sensitive fire weather index (FWI) as at

present. By reviewing some of the assumptions incorporated in this thesis, future model reliability can be improved. As an example, the assumption which at present implies that a singular air strike by a group of three airtankers will be effective, could be adjusted in accordance with updated airtanker effectiveness functions specific to the type and capability of aircraft involved. In this regard the present linear distance decay function warrants exploration in an effort to better define the rate and/or extent of declining airtanker effectiveness potential over distance. This would probably be defined according to different combinations of aircraft type and retardant capacity, fire hazard, and protection priority. This could lead to an exponential distance-effectiveness function for each combination of variables. Additional consideration will have to be given to quantifying "value-at-risk" measures in an effort to better distinguish aerial attack priorities on a more meaningful rating than the present straight line numerical scale based on protection priorities.

This thesis has served to describe a particular fire control problem in Alberta and has followed through with the adoption of a simple location-allocation routine to provide some insight into solving the problem from a research standpoint. A comprehensive analysis and discussion of the results indicates that, although not immediately or directly applicable to day-to-day decision-making procedures in an aerial fire control program, modifications and improvements

to make the model more operationally applicable are foreseen.

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APPENDIX 1

DESCRIPTIVE DANGER CLASSES AND SEVERITY RANGES FOR THE THREE FIRE BEHAVIOUR INDICES

DESCRIPTIVE DANGER CLASSES	FIRE BEHAVIOUR INDICES* ISI	BUI	FWI
LOW	0.0 - 1.0	0 - 25	0.0 - 0.1
MODERATE	1.1 - 3.0	26 - 50	0.2 - 8.0
HIGH	3.1 - 8.0	51 - 87	8.1 - 16.0
VERY HIGH	8.1 - 16.0	76 - 100	16.1 - 25.0
EXTREME	16.1+	101+	25.1+

* ISI = INITIAL SPREAD INDEX
BUI = BUILDUP INDEX
FWI = FIRE WEATHER INDEX

APPENDIX 2

AIRTANKER PERFORMANCE SUMMARY

(A) PBY-5A Canso

Dimensions: length = 19.5 m

: wing span = 31.7 m

: height = 5.7 m

Take-off roll: land = 1100 m

water = 1500 - 2000 m

Normal operating cruise speed: 185 km/hr

Retardant capacity under normal operating conditions:

land = 3000 1 long-term retardant

water = 3800 1 water or short-term retardant

This is a Second World War vintage amphibious aircraft, first converted for fire bombing purposes in 1961. There are currently two common Canadian tanking systems built into these aircraft--the Field and Fairey systems. Because of its ability to repeatedly pick up loads of water from nearby lakes, its role as an airtanker is assured for some time to come, particularly in the many areas of Canada where water sources are almost limitless. In the land-based mode the PBY is often dispatched with an initial load of chemical (long-term) fire retardant. In the skimming mode, while picking up water from lake surfaces, most Cansos have an on-board injection system which permits the addition of

water modifying chemicals to the load, usually in the form of thickening compounds.

(B) Douglas B-26 Invader

Dimensions: length = 15.5 m

: wing span = 21 m

: height = 5.6 m

Take-off roll = 1600 m

Normal operational cruise speed = 385 km/hr.

Retardant capacity under normal operating conditions: 3650 l

This is a high speed medium bomber of late WW II and Korean War vintage. Since converted to its present role as an airtanker this aircraft has become quite popular in Alberta, British Columbia, Yukon and Northwest Territories primarily because of its speed and retardant capacity. The two-door version is the most common B-26 delivery system in use in Canada and, when accurately placed, its load of chemical fire retardant can effectively retard the early stages of a fire's growth. This airtanker is well suited to its role as a rapid initial attack tool; however, its dependency upon designated reload bases is a limiting factor when used on rapid spreading or large wildfires.

APPENDIX 3

AIRTANKER BASE CODE SUMMARY

AIRTANKER BASE	FOREST	NUMERICAL CODE
FOOTNER LAKE	FOOTNER LAKE	1
FORT McMURRAY	ATHABASCA	2
SLAVE LAKE	SLAVE LAKE	3
LAC LA BICHE	LAC LA BICHE	4
PEACE RIVER	PEAVE RIVER	5
FOX CREEK	WHITECOURT	6
GRANDE PRAIRIE	GRANDE PRAIRIE	7
EDSON	EDSON	8
ROCKY MTN. HOUSE	ROCKY - CLEARWATER	9
CALGARY	BOW - CROW	10
LETHBRIDGE	BOW - CROW	11

APPENDIX 4

DAY-DATE RELATIONSHIP FOR 1974 TIME PERIODS

TIME PERIOD	DATES	NUMBER
135 - 143	MAY 15 - 23	1
144 - 149	" 24 - 29	2
150 - 155	MAY 30 - JUN 4	3
156 - 165	JUNE 5 - 14	4
166 - 169	" 15 - 18	5
170 - 171	" 19 - 20	6
172 - 173	" 21 - 22	7
174 - 174	" 23	8
175 - 175	" 24	9
176 - 176	" 25	10
177 - 177	" 26	11
178 - 179	" 27 - 28	12
180 - 182	JUNE 29 - JULY 1	13
183 - 186	JULY 2 - 5	14
187 - 196	" 6 - 15	15
197 - 197	" 16	16
198 - 207	" 17 - 26	17
208 - 208	" 27	18
209 - 211	" 28 - 30	19
212 - 216	JULY 31 - AUG. 4	20
217 - 218	AUG. 5 - 6	21
219 - 227	" 7 - 15	22
228 - 230	" 16 - 18	23

APPENDIX 5

ALBERTA ENERGY AND NATURAL RESOURCES FIRE REPORT CODING FORM

01 TRANSCODE
1 DELETE
2 NEW
3 CHANGE

02 FIRE NUMBER
FOREST DISTRICT — YEAR — NUMBER

03 SIZE CLASS
1 A — 3 C — 6 E
2 B — 4 D — 6 XA

04 FIRE ORIGIN
LS — SEC — TWP — RGE — M

05
1 PROTECTION AREA
2 RURAL FIRE AREA
3 OTHER

06 OWNERSHIP OF LAND
1 CROWN LAND
2 INDIAN RESERVE
3 FEDERAL
4 PRIVATE
5 PROV OF B C
6 PROVINCE OF SASK
7 OTHER
8 METIS COLONY
9 N W T

07 GENERAL CAUSES
0 OTHER INDUSTRIES
1 LIGHTNING
2 SETTLEMENT
3 WOOD INDUSTRIES
4 RAILROAD
5 PUBLIC PROJECT
6 RECREATION
7 INCENDIARY
8 MISC KNOWN
9 UNKNOWN

08 CAUSE CLASS
1 OWNER (PRIVATE)
2 PUBLIC EMPLOYEES
3 LOCAL RESIDENT
4 SEASONAL WORKER
5 TRANSIENT
6 CHILDREN
7 OTHERS-KNOWN
8 UNKNOWN

09 SPECIFIC CAUSE

10 DISCOVERY AGENT
1 LOOKOUT
2 FOREST OFFICER
3 A F S EMPLOYEE
4 A F S AIRCRAFT
5 OTHER AIRCRAFT
6 FOREST LICENSEES, PERMITTEES
7 PUBLIC
8 OTHER GOV'T OFFICIALS
9 OTHER

11 LOOKOUT

MILES TRAVELLED FROM POINT OF ASSEMBLY TO POINT OF INITIAL ATTACK
13 TWO WHEEL DRIVE
14 FOUR WHEEL DRIVE
15 TRACKED VEHICLE
16 HELICOPTER
17 FIXED WING
18 WALKED
19 OTHERS

12 REPORTED TO
1 RANGER OR FOREST OFFICER
2 OTHER A F S EMP
3 OTHER PUBLIC EMP
4 OTHERS

ACTUAL TIME
20 STARTED — HR. DAY MO
21 DISCOVERED — HR DAY MO.

TIME LAPSES, FROM
22 START TO DISCOVER
23 DISCOVER TO REPORT
24 REPORT TO GETAWAY
25 GETAWAY TO ATTACK
26 ATTACK TO CONTROL
27 CONTROL TO EXTINGUISH

FUEL BURNING AT ORIGIN
28 PRIMARY — 1 2 3 4 5 6 7 8 9 D
1 TIMBER, 2 GRASS, 3 BRUSH, 4 SLASH, 5 SNAGS, 6 D LOG, 7 DUFF, 8 LICHEN, 9 MOSS, D OTHERS
29 SECONDARY — 1 2 3 4 5 6 7 8 9 D

30 COVER TYPE
1 SPRUCE
2 PINE
3 DECID
4 MUSKEG
5 BOG
6 BRUSH
7 GRASS
8 RECENT BURNS
9 CLEAR CUTS
D OTHERS

WEATHER AT TIME OF INITIAL SUPRESSION
31 GENERAL — 32 OVER FIRE
1 NO PRECIPITATION
2 RAIN SHOWERS
3 CONTINUOUS RAIN
4 GROUND FOG
5 DRIZZLE
6 THUNDERSTORM
7 HAIL
8 SNOW SHOWERS

33 WIND DIRECTION
1 NORTH
2 NORTHEAST
3 EAST
4 SOUTHEAST
5 SOUTH
6 SOUTHWEST
7 WEST
8 NORTHWEST

34 AVERAGE WIND SPEED
35 WIND CHARACTER
1 VARIABLE
2 GUSTY
36 ADMC
37 FWI

INITIAL ATTACK TAKEN BY (ACTUAL NUMBER)
38 MEN - TOOLS
39 DOZERS
40 FIXED WING BOMBERS
41 HELICOPTERS
42 POWER PUMPS
43 TANKERS
44 OTHERS

45 MAXIMUM NUMBER OF MEN

SIZE
46 AT DISCOVERY
47 INITIAL ATTACK

FIRE AREA
48 RURAL FIRE AREA
49 TOTAL CROWN LAND
50 PRIVATE LAND
51 TOTAL
52 PRODUCTIVE
56 POTENTIAL
57 NON-PRODUCTIVE

VOLUME LOSS (CU. METRES)
58 CONIF SAWTIMBER
59 CONIF SMALL WOOD
60 DECID SMALL WOOD
62 DECID SAWTIMBER

VALUE LOSS
63 PROD
64 POT PROD
65 TOTAL

61 SUPRESSION COSTS

Source: *Alberta, Energy and Natural Resources, Forest Service.*

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